For Reference

NOT TO BE TAKEN FROM THIS ROOM

A REGIME THEORY ANALYSIS OF SEDIMENT TRANSPORT

R. Bryan Erb

Ex libris
universitatis
albertaensis

UNIVERSITY OF ALBERTA

QUAECUMQUE VERA

Digitized by the Internet Archive
in 2018 with funding from
University of Alberta Libraries

https://archive.org/details/erb1955

ABSTRACT

Existing data on sediment transport in flumes are analysed by the methods of Regime Theory. This analysis modifies two of the regime equations to include sediment transport. One of these modified equations connects bed factor to its causes, the other generalizes the King equation for slope. These relations can be readily used to compute the quantity of sediment that is being transported by a channel in regime.

5/5
55
7

THE UNIVERSITY OF ALBERTA

A REGIME THEORY ANALYSIS OF SEDIMENT TRANSPORT

A DISSERTATION
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

FACULTY OF ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING

by

R. BRYAN ERB

UNDER THE DIRECTION OF
PROFESSOR T. BLENCH

EDMONTON, ALBERTA

APRIL, 1955

ACKNOWLEDGMENT

The writer wishes to express his thanks to Professor T. Blench for his interest, guidance and constructive criticisms throughout the present study.

What we know here is very little, but what we are ignorant of is immense.-

.... Laplace.

TABLE OF CONTENTS

1. Introduction 1
    - The Problem of Sediment-Bearing Channels 1
    - Importance of the Study 1
    - Methods of Approach 2

2. The Nature of Sediment Transport 3
    - The Modes of Sediment Transport 3
    - Bed-Load Movement 4

3. The Characteristics of the Transported Material 7
    - Properties of the Transported Material 7
    - Natural Sands 9
    - Significance of a Natural Grading 12

4. Regime Theory 13
    - History of Regime Theory 13
    - Outline of Regime Theory 16
    - The Application of Regime Theory to Sediment Transport 17

5. The Regime Analysis of Sediment Transport 19
    - Data Used in the Analysis 19
    - Method of Analysis 22
    - Results 24
    - Suspended Load 30

6. A Comparison of Methods of Describing Sediment Transport 32
    - Critical Tractive Force Methods 32
    - The Einstein Bed-Load Function 33
    - The Meyer-Peter Method 33
    - The Regime Theory Approach 34

7. A Suggested Programme for Future Research 35

8. Summary 37

Bibliography 38

Appendix I Notation 41

Appendix II Figures 6 to 29 43

LIST OF FIGURES

1. Shape of Bed Dunes 6

2. Relation of Dispersion to Settling Velocity, River and Beach Sands 11

3. Test of $F_b = F_{bo} (1 + AC^n)$ 27

4. Values of 'A' in the Bed Factor Equation 28

5. Variation of King's Coefficient with Sediment Charge 29

6 - 13 Test of the Bed Factor Equation for Gilbert Sands 43-50

14. Test of the Bed Factor Equation for Straub Sand 51

15 - 18 Test of the Bed Factor Equation for U.S. Corps of Engineers' Sands 52-55

19 - 26 Variation of King's Coefficient with Sediment Charge for Gilbert Sands 56-63

27. Variation of King's Coefficient with Sediment Charge for Straub Sand 64

28. Variation of Absolute Rugosity with Suspended Sediment Charge 65

29. Effect of Suspended Load on Viscosity 66

I. Introduction

The Problem of Sediment-Bearing Channels

In the adaptation of his environment man often has to consider the problems of controlling natural waterways and of producing artificial ones. Many of these waterways are of the sediment-bearing type, that is, channels which carry a load of material similar to that which forms their boundary. Such channels exhibit the ability to adjust their width, depth and slope in accordance with the characteristics of the sediment they carry and the prevailing discharge, regardless of any conditions that might have been initially imposed upon them. It is with these 'alluvial' channels that difficulties are most often encountered because of this self-adjustment in the face of imposed conditions. If natural waterways are to be controlled it must be possible to anticipate the adjustment which they will undergo. And if artificial waterways are to run without change they must be designed initially to satisfy the equilibrium conditions to which they would eventually adjust themselves. Such an understanding of alluvial channels will thus require:

(a) a description of the laws of channel formation, and

(b) a description of the sediment transport mechanisms upon which these laws depend.

Importance of the Study

The study of alluvial channels and of sediment transport has important applications to the control of rivers and to river basin development, including irrigation.

For the control of rivers, it is necessary to be able to predict the behavior of rivers with respect to meandering, bank erosion and channel formation for the purposes of navigation, protection of land and the construction of bridges, tunnels and docks.

River basin development includes the very important studies of irrigation, canal design and operation, flood, erosion and pollution control, water supply and power.

An understanding of alluvial channels is also of interest to geologists, as it gives an indication of the origin and history of land forms.

Methods of Approach

The study of alluvial channels was pursued on two main lines. One originated in field work, the other in laboratory work.

The field approach involved observations on canal systems which had reached equilibrium by self-adjustment, and led to the formulation of Regime Theory (Refs. 1,2) which describes the results of this self-adjustment.

The laboratory approach was concerned with sediment transport experiments in flumes, and the search for ways of describing the mechanisms of this transport upon which the laws of channel formation depend, (Refs. 3,4,5,6).

The present study aims at a coalition of these two approaches. Regime theory, describing as it does the characteristics of self-formed channels, should apply also to flumes which have adjusted themselves. That is, it should be possible to extend Regime theory

to include flume observations and thus to describe the transport of sediment, which can be measured in the laboratory but not in the field. This extension should yield sediment transport relations which are modifications of the regime laws and as such should give useful indications of the behavior of full scale channels.

2. The Nature of Sediment Transport

The Modes of Sediment Transport

The geological definition of sediment concerns fragmental material which has been deposited by some agent, generally water. We shall, however, consider a more general definition and include as sediment that material which is still in the process of being transported. For the purpose of this study we shall define as follows the modes of sediment transport, (Ref. 6):

Stream load All material being transported by the stream.

Floating load The part of the stream load which is transported by flotation. This term generally applies to trees and drift but it should be noted that sand can also be transported by flotation, (Ref. 7). There is, at present, no data to indicate whether or not this is an important means of transportation, but it seems likely that, as far as rivers are concerned, it is not. It may, however, account for the grading in sand size with distance from the shore observed in lakes.

Quasi-sedimentary load That part of the stream load which is transported in solution or in colloidal suspension. This part of the load has, so far as is known,

no effect on the formation of the stream.

Sedimentary load All material, generally of a mineral nature such as sand or gravel, transported by hydraulic entrainment. This load can conveniently be divided into two categories:

(a) Bed load That portion of the total load which moves along and can constantly be identified with the bed. This does not mean that bed load is continually in contact with the bed, but rather that, in any short period of time, a particle will be either at rest on the bed, rolling along the bed, or in the process of making a jump over part of the bed. This jumping is termed 'saltation' and is definitly a feature of the bed load, (Refs. 3,8).

(b) Suspended load That portion of the sedimentary load that travels in suspension. This mode of transport is distinct from transport by colloidal suspension in that the particles are supported by the vertical components of the turbulent velocity fluctuations rather than by the action of molecules.

Bed Load Movement

There are three known phases of bed load movement, (Ref. 3). The most common is the dune phase of motion associated with subcritical flow. In this phase of motion the bed material, generally sand or gravel, moves along in a series of small waves or dunes which progress downstream. The appearance of these dunes (Fig. 1) will be familiar to anyone who has observed canals or flumes.

As the flow approaches and exceeds the critical the dunes vanish and the flow is in planes parallel to the bed. This phase of flow has been described by Gilbert (Ref. 3) as 'smooth' but since this term infers laminar flow we shall follow Blench (Ref. 9) in calling this phase of motion 'sheet flow'.

As flow becomes increasingly super-critical dunes reappear. Their form is, however, unlike that of the dunes associated with sub-critical flow in having a more nearly sinusoidal cross section, and in progressing upstream. This retrograde motion is caused, of course, by scour on the downcurrent face of the dune and deposition of material on the upcurrent face of the following dune. Since these dunes move upstream they have been given the name ' antidunes' by Gilbert and we shall refer to them as such.

The actual mechanism of bed load transport is very poorly understood; however, it can be described qualitatively for the dune motion phase.

Referring to Figure I, the main part of the fluid flow follows a sinusoidal path along the boundary ABD where BD is a surface of discontinuity, that is, sheet vortices. The region BCD encloses an eddy and thus motion along the face CD will be retrograde. A is essentially a stagnation point of the flow, and B may be a point at which the boundary layer separates. The face AB is the active one as concerns transport by sliding or rolling, the grains moving up the slope under the action of the shearing forces at the boundary. After the point of separation, B, the grains simply roll down the incline BC, which slopes at, nearly, the angle of repose of the bed material.

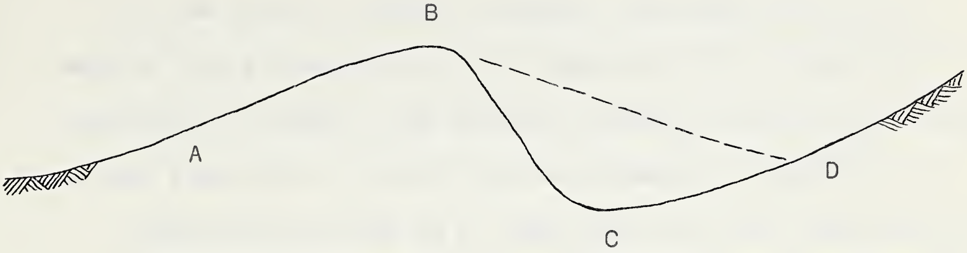


FIGURE 1.

Saltation occurs when a particle is rolled against an undisturbed grain that lies in its path and is accelerated upward and forward by the hydrodynamic force. Within limits, the larger the obstacle over which the particle must jump the greater the acceleration and the longer the hop. In such a jump a particle can travel many times its own diameter clearing several dunes in its leap. When one of the saltating particles lands on the up-current face of a dune it initiates further movement by causing a 'splash' of particles each of which will make a short hop. The motion of particles in aeolian dunes is very similar; Bagnold (Ref. 10) gives an excellent description of this type of transport.

Gilbert (Ref. 3) describes other types of motion such as scour caused by local vortex action, but these seem to be important only in rather specialized circumstances.

3. The Characteristics of the Transported Material

In the study of sediment transport the properties of the material being transported play an important part. It would be desirable to include in the sediment transport relations the effects of such properties in terms of as few parameters as possible.

Properties which may be of importance are size, shape, density hardness and grading. Other sediment properties such as void ratio and plasticity are of no importance to our study since we are considering free particles.

Properties of the Transported Material

Size Particle size is probably the most important property of the transported material. The definition of size when dealing with a mixture is arbitrary. Some investigators use whatever measure fits best the results of their experimental work, such as the size for which the aggregate weight of all smaller grains is, say, 65% of the total weight. However, the most convenient measure of the size of a mixture is the diameter of the median grain and it is this that we shall mean when referring to sediment size.

Shape The shape of the particles is important in both suspended and bed load transport. The suspended load transport is related to the settlement velocity of the particles and this depends on their shape (Ref. 11). Particle shape also determines, in part, whether a grain will slide, roll or saltate (Ref. 8). The definition of particle shape is a difficult problem (Ref. 23), and the effect of shape on sediment transport can not be stated.

Specific Gravity The specific gravity of most sediments in the size range of sand and gravel is, very nearly, 2.70. Since all observations in nature and most laboratory experiments have been on such material, the effect of specific gravity on the sediment transport relations has not been apparent. Some experimental work has been done covering a large range of specific gravity (Ref. 12), but since the original data are not available this property has been neglected in the present analysis.

Hardness In the transportation process the products of erosion which form the stream load are rolled and bounced along the bed. Under this action soft material will be broken down into particles which will either be small enough to go into suspension or hard enough, individually, to resist further decomposition.

Grading The behavior of a sediment mixture will depend on the distribution of particles about the median size as well as on the actual median size, hence the grading of the particles must be included in the description of a mixture. As we shall see, most river sands follow a definite grading which can be defined as a first approximation by a measure such as the standard deviation. That some unique grading of the bed material should result from the transportation processes may be explicable on the grounds that small particles will 'hide' behind the larger ones, the very smallest will go into suspension, and the heavy particles will gradually sink down in the bed since the stream is not capable of moving them.

The most important sediment properties as concerns transport are then size, shape and grading. Shape must be omitted from consideration because it is not known how to include its effect, but size and grading must be specified in the sediment transport relations.

Natural Sands

It has long been recognized by geologists (Refs. 13,14) that many sands have size distributions that follow logarithmic frequency laws. This means that particle diameter is a property in which rate of change rather than amount of change is fundamental. It is convenient to display size distributions as plots on logarithmic probability paper since this presents logarithmic frequency functions as straight lines.

This apparent natural grading of sands had received little publicity in Engineering literature until the independent work of Blench (Ref. 15). For the purposes of describing bed load Blench considered as important only that part of the material between 2% and 98% of the total. Small percentages at the ends of the grading will be of importance in some applications, for example 1% of clay in a fine sand changes completely its cohesion and plasticity, but should not affect greatly the transport properties of a sediment.

As a matter of course in the study of flume data, the mechanical analyses of the sediments used were plotted on logarithmic probability paper to see how closely they conformed to the natural grading described in reference 15. It was observed that the slope of the

line, which is a measure of the standard deviation on a logarithmic scale, varied with the median grain size. Further data, given in Table I, confirmed this and a correlation was found between the 'dispersion', as we shall call this logarithmic probability slope, and the settling velocity of the median size particle. Figure 2 illustrates the relation between these quantities. Having regard for the likelihood of simple indices the equation of the best fit line may be taken as

$$\delta = 2.6\, V_s^{5/12} \qquad \text{......(3.1)}$$

where δ is the dispersion about the median size. This measure can be related to other measures of the distribution such as the sorting coefficient, S_o, used by the geologists, that is

$$S_o = \sqrt{Q_1/Q_3}$$

where Q_1 and Q_3 are, respectively, the first and third quartile sizes. A scale of sorting coefficient is included on Figure 2 for comparison. Similarly δ could be related to other measures of the distribution such as Hazen's uniformity coefficient, D_{60}/D_{10}.

In view of the relationship described by equation (3.1), the specification of median particle size for a sand fixes the distribution about the median and thus a single measure, D, will describe the two most important properties of a natural sand, size and grading. It is possible that particle shape affects this relation, perhaps in the value of the coefficient. Specific gravity may also affect the distribution, particularly if there is a predominance of heavy particles at one end of the range.

TABLE I

RELATION OF DISPERSION TO SETTLING VELOCITY

Source Reference	Material Designation	D mm.	V_s* cm./sec.	δ
6	1	0.42	6.2	0.765
	2	0.44	6.5	0.566
	3	0.48	7.2	0.466
	4	0.43	6.3	0.664
	5	0.40	5.8	0.588
	6	0.33	4.7	0.321
	7	0.28	3.8	0.453
	8	0.18	2.1	0.316
	Mile 27	1.78	26.5	1.13
	Mile 1069	0.182	2.1	0.465
		0.13	1.27	0.341
		0.158	1.70	0.392
7	'Black sand'	0.157	1.7	0.249
13	II	0.267	3.6	0.365
14	E	0.255	3.4	0.476
	C,D	0.137	1.37	0.238
15	-	0.51	7.7	0.379
		0.34	4.8	0.326
		0.22	2.73	0.303
16	Mountain Cr.	0.90	13.9	0.707
	Goose Creek	0.29	4.0	0.46
17	-	0.20	2.4	0.384
18	'Coarse'	0.42	6.2	0.507
	'Fine'	0.285	3.9	0.311
19	'Coarse'	0.422	6.2	0.500
	'Fine'	0.272	3.7	0.366
20	Mixture A	2.62	35.5	1.23
	Mixture C	1.15	17.6	0.846
21	SS 10	1.00	15.5	0.825
	ns Tp	1.80	26.7	0.966
	'Dunblane'	0.099	0.78	0.282

---

* From Reference 22, Figure 5, page 41.

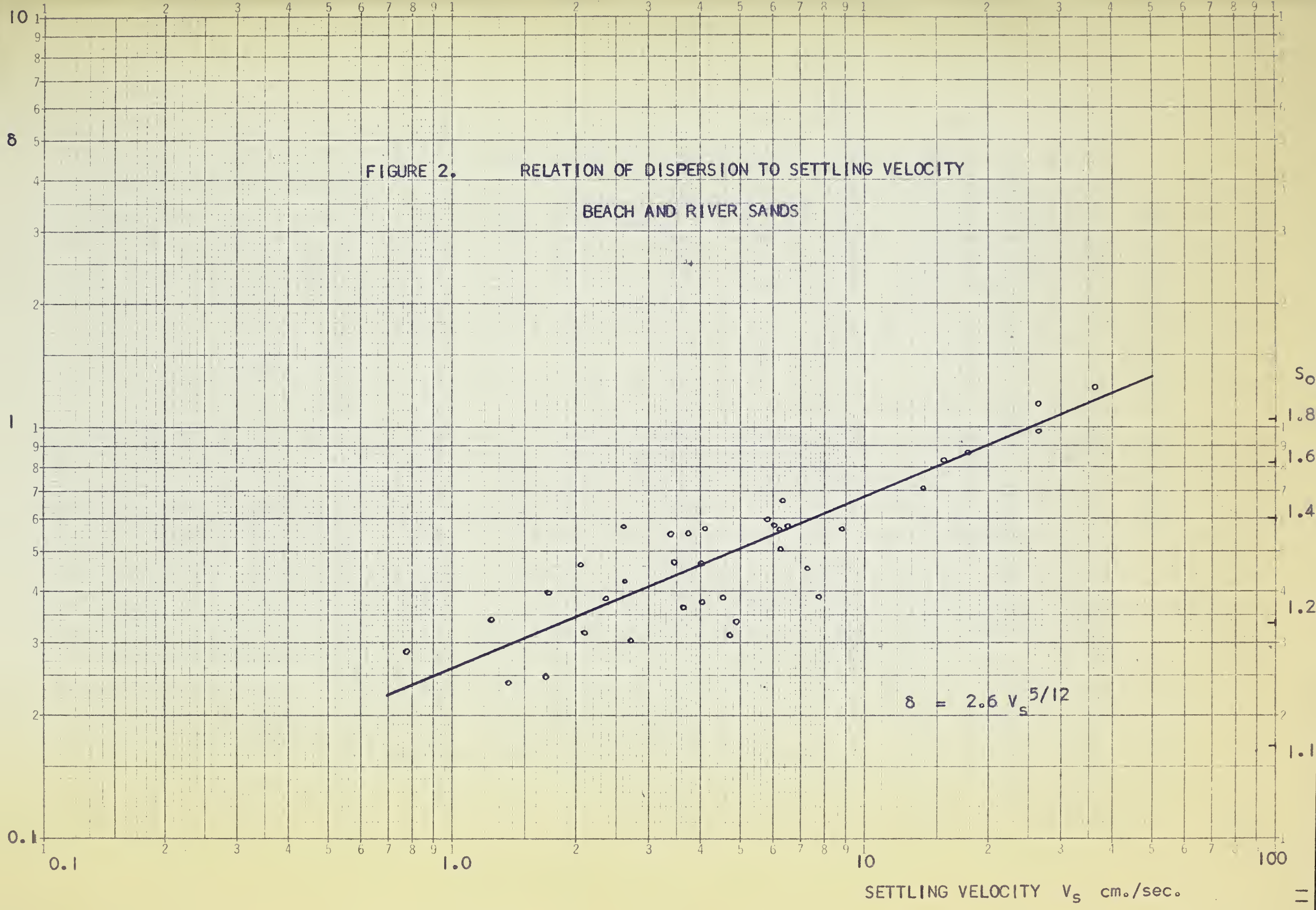


FIGURE 2. RELATION OF DISPERSION TO SETTLING VELOCITY

BEACH AND RIVER SANDS

Significance of a Natural Grading

The main value to the engineer of this natural grading and the relation between dispersion and settling velocity is that it allows the inclusion of material properties as a single parameter in the sediment transport relations. Also, it gives a means of determining whether a sand, during the course of a flume experiment, is likely to change its constitution in trying to approach the natural grading.

This grading property is useful to the geologist as well since slight variations in the form of the grading curve give an indication of the origin of a material. Such use of the curve is, however, based on the assumption that materials of the same origin will produce the same grading curve; that is, the parameters describing the curve also describe fully the characteristics of the material. To be used in this capacity the grading must be described more accurately than we have attempted to describe it. For example, the small portions at the ends of the grading must be included and this can be done by considering the skewness and kurtosis of the distribution curve. This method of describing sediment has been intensively studied for the purpose of classifying sediment deposits (Ref. 23).

4. Regime Theory

Since the basis of our approach to the problem of sediment transport is the theory of regime channels we shall give a brief treatment of this theory and its background.

History of Regime Theory (Refs. 1,2)

The distinguishing feature of a channel which carries a load of sediment is its ability to adjust, within limits, its width, depth and slope in accordance with the characteristics of the sediment and the prevailing discharge. The relations which describe this adjustment are difficult to determine from observations on rivers because of large fluctuations in discharge and complications introduced by meandering and non-homogeneity of the banks and bed. Canals, however, can be considered to be rivers without meanders whose discharge is very nearly constant, and thus we might expect that the study of canals would lead to a statement of the relations governing the adjustment.

The world's largest canal systems were constructed in India in the latter part of the nineteenth and the early part of the twentieth centuries. In complete ignorance of the 'adjustment laws' these canals were designed following rigid boundary practice with but one equation of flow. It was very soon observed, however, that these sediment-bearing canals proceeded to alter their width, depth and slope until they achieved a state of equilibrium.

The first approach to the problem was made by Kennedy in 1895. He selected a number of canals which had reached equilibrium and

looked for relations between their width, depth and velocity. His study led to the equation

$$V = 0.84\ d^{0.64}$$

where V is the mean velocity of flow for a section of mean depth d.

This equation along with the flow formula of rigid boundary hydraulics gave only two equations with which to treat three variables, that is, it was permissible to design channels wide and shallow or narrow and deep. This was an advance on the previous method, but left one degree of freedom still undescribed.

In 1919 Lindley linked bed width and depth to velocity and proposed the formulas

$$V = 0.95\ d^{0.57}$$
$$V = 0.57\ b^{0.335}$$

in which b is the channel breadth. Lindley also recognized that the coefficients in these relations were functions of the sediment characteristics.

The next advance was the introduction in 1929 by Lacey of specific 'silt factors', and a unique relation for the slope of 'Regime Canals' as these self-adjusted channels had come to be called. Lacey also recognized that the dynamical meaning which must lie behind these relations would favor simple exponents such as 1/2, 1/4 etc. He made a retrograde step, however, in introducing hydraulic radius R and wetted perimeter P in place of Lindley's depth and width. If S is the slope, ν the viscosity and f a 'silt factor' then Lacey's equations may be written in the form

$$V^2/gR \quad \alpha \quad f$$

$$P/R \quad \alpha \quad V/(\nu g)^{1/3}$$

$$V \quad \alpha \quad (VR/\nu)^{1/6}(V^2/gR)^{-1/3}\sqrt{gRS}$$

The difficulty with these equations is that the silt factor includes the characteristics of both the bed and sides, two parts of a channel which are very different and in different phases of flow.

The next major advance was the introduction of side factor by Blench. He also returned to the individual specification of the bed and sides and defined parameters associated with them as

$$V^2/d = F_b \quad \text{a bed factor, and} \qquad \ldots\ldots(4.1)$$

$$V^3/b = F_s \quad \text{a side factor.} \qquad \ldots\ldots(4.2)$$

Blench also pointed out the dynamical meaning of these equations. If bed factor is made non-dimensional (by dividing g into V^2/d) it is seen to be the Froude number in terms of the channel depth. The side factor can be made non-dimensional by multiplication by $\rho^2\nu$ which gives a measure of the square of the tractive force along the sides provided that the stage of flow on the sides is 'smooth'.

Finally, a dynamically satisfying slope formula was obtained by King. This formula can be written

$$V^2/gdS = 3.63\ (Vb/\nu)^{1/4} \qquad \ldots\ldots(4.3)$$

in which the value of the coefficient is the result of observations on many canal systems. This equation is a generalization of the Blasius equation for smooth flow in pipes with the Reynold's number expressed in terms of the channel width.

Outline of Regime Theory

Modern Regime Theory gives three equations with which to describe the three degrees of freedom of sediment-bearing channels. The basic equations (4.1,2,3) can be expressed as design equations which give explicitly depth, width and slope as functions of the discharge, which will be known, and the side and bed factors which depend on the characteristics of the material which forms the sides and the bed.

The exact conditions for which Regime Theory is supposed to apply are given by Blench in reference 24. As stated therein the conditions are very stringent, but Blench has shown that they can be relaxed even to the extent of applying with sucess to a tidal estuary (Ref. 25). If these conditions are satisfied then the problem of canal design becomes one of determining the bed and side factors since discharge will always be known. It is most important that the slope be correctly estimated, whereas small changes in depth and width can be tolerated. Since the side factor appears in the slope formula raised to the 1/12 power, its estimation can afford to be somewhat approximate. Ultimately then, the design of a canal depends on a knowledge of the correct bed factor. This bed factor will be some function of the sediment characteristics and, as we shall see, of the charge, that is, the ratio of the sediment transported to discharge.

In classical Regime Theory the only guide to the estimation of bed factor was Lacey's "rough empirical rule"

$$F_b = 1.9 (D)^{1/2} \qquad \text{.......(4.4)}$$

in which D is the median grain size measured in millimeters.

This rule was derived from values of bed factor for a series of sediments in the size range of normal sands, that is, median grain diameter on the order of 0.5 mm, and one very questionable value of bed factor for four inch gravel.

We have seen, then, that Regime Theory describes the equilibrium of channels which carry a sediment load and adjust their boundaries in accordance with the nature and quantity of the transported material.

The Application of Regime Theory to Sediment Transport

The value of Regime Theory to the present study lies in the basic assertion that since the regime equations are correlations between the equilibrium characteristics of self-adjusted canals and the nature of the 'water-sediment complex', as Blench calls the transporting fluid with its sediment admixture, they should also be expressions of the laws of sediment transport. That is to say, since canals are formed in accordance with the laws of sediment transport, the regime equations which describe this formation should be capable of modification to describe the relevant sediment transport.

The first attempt to include the effect of transported material on canal behavior was made by Inglis (Ref. 2). Inglis started with the assumption that the charge and the settlement velocity should be considered together, and produced the equation

$$\frac{bg^{1/5}}{Q^2} \quad \alpha \quad \left(\frac{Q}{D^{5/2}g^{1/2}}\right)^{n_1} \left(\frac{CV_s}{(\nu g)^{1/3}}\right)^{n_2}$$

The validity of this formula is questionable, however, since for the important case of vanishingly small charge it indicates channels of zero slope and infinite depth.

The next step was made by Blench (Ref. 25) who proposed, on the basis of flume experiments, that charge be included in the bed factor equation in the form

$$F_b = 1.9\sqrt{D}\,(1 + 0.135C). \qquad \ldots\ldots (4.5)$$

Blench later analysed a sample of the Gilbert data (Ref. 3) and proposed (Ref. 9) two modifications to the regime equations viz.

$$F_b = F_{bo}\,(1 + 0.068\,C) \qquad \ldots\ldots(4.6)$$

$$V^2/gdS = 3.63\,(1 + C/400)\,(Vb/\nu)^{1/4} \qquad \ldots\ldots(4.7)$$

which apply in the sub-critical range of flow, and

$$F_b = 32.2 + 0.056\,(C - C_c) \qquad \ldots\ldots(4.7)$$

for sheet flow, in which C_c is a 'critical charge'.

The object of the present study is the complete analysis of existing data with a view to stating more exactly, if possible, the modified regime equations which describe the formation of sediment-bearing channels.

5. The Regime Analysis of Sediment Transport

The application of regime principles to observations on the rate of transport of sediment should give modified forms of the three independent regime equations. Two of these modified equations should relate bed and side factor to their causes and the third should be a generalization of the King equation for slope.

There have been attempts to measure the sediment load of streams and canals (Ref. 16) but the accuracy of the measurements is such that the data are of little use and thus a complete analysis is not possible.

For the present study the data of flume experiments have been used. The rigid sides of flumes eliminate one degree of freedom, however, so that an analysis of such data will yield only the two equations describing the adjustment of depth and slope.

In the last 50 years many flume experiments have been undertaken, but the results of most of these are not suitable for analysis because either some essential part of the data was not recorded, or the individual runs were not allowed to reach equilibrium. Probably the only complete set of data is that of the Gilbert-Murphy experiment (Ref. 3), which is the main basis of the present study. The other sources of data are experiments performed by the U.S. Corps of Engineers (Ref. 6), Straub (Ref. 17) and Blench (Ref. 27).

Data Used in the Analysis

A. The Gilbert-Murphy Experiment (Ref. 3)

This classic experiment was a systematic study of sediment

transport designed to investigate individually the effects of charge, discharge, flume width and sediment size in determining the depth and slope for equilibrium. Different grades of sediment were obtained by splitting a river sand into the fractions retained between adjacent sieve sizes.

This extensive study involved six widths of channel, six values of discharge and eight grades of sediment. For each combination of these three variables the charge was varied, resulting in the bed configuration ranging from dunes through sheet flow to antidunes. Not all possible combinations were used, the actual number being 130 for each of which a series of measurements of load, slope and depth was made. The separate determinations of load, slope and depth numbered about 900.

This set of data is very nearly complete although the configuration of the bed is not specified for some of the runs. In the present analysis we have considered the whole of the data including those for which the bed configuration is unspecified and those in a 'transition' phase.

B. The U.S. Corps of Engineers' Experiment (Ref. 6)

In conjunction with a study of the lower Mississippi the U.S. Corps of Engineers undertook a series of flume studies on 'River Bed Materials and Their Movement'. The materials used in these tests were naturally graded river sands from various sources along the Mississippi. The experiment was mainly concerned with determining the flow necessary to initiate bed movement, but at higher discharges 'riffles', as they were termed, were allowed to develop. The runs

for which the bed condition is designated as 'general riffles' were those considered in the present analysis. The runs were of very short duration and complete regime was, in all probability, not reached; however some of the results are still of interest.

C. Flume Studies in Conjunction with Fraser River Model

In conjunction with model experiments on the Fraser a flume study of bed movement was undertaken by Blench (Ref. 27). The main interest of this work to the present study is the observations on the time necessary for a flume to run to regime. It was noted that in some cases eighty hours of running were necessary before the depth became constant.

Present work at the University of Alberta (Ref. 18) indicates that even the figure of eighty hours may be optimistic. From tests on a small flume, run to regime with vanishingly small charge, it has been found that a week or more may be required before bed movement stops.

D. Transportation Characteristics of Missouri River Sediment

In this study two series of tests were performed on a fine, natural sand from the Missouri River, (Ref. 17). One series of tests involved a constant rate of transportation, the other a constant discharge. Since the runs were of several hours duration it is likely that regime was nearly established.

Method of Analysis

Natural canals, such as those in India for which Regime Theory was conceived, carry very little sediment in the form of bed load, probably not more than two or three thousandths of one percent. Thus an analysis of canal data has never revealed the dependence of bed factor on charge, but only on sediment characteristics. The bed factor obtained from canal data will be, very nearly, F_{bo}, the bed factor for vanishingly small charge. The actual bed factor for a channel carrying a load will be modified by some function of charge which vanishes with charge.

From dimensional analysis Blench (Ref. 9) has developed possible forms of the modified equation. Of these the simplest is

$$F_b = F_{bo} (1 + f_1 (C)) \qquad \text{.......(5.1)}$$

where F_{bo} is a function of D alone. It is also possible that the relationship is of the form

$$F_b = F_{bo} (1 + f_2 (D,C)) \qquad \text{.......(5.2)}$$

The actual analysis involved the computation of bed factor from measured values of depth, discharge and width determined in the various flume studies. The value of F_{bo} was estimated and a plot made of

$$\frac{F_b - F_{bo}}{F_{bo}}$$

against charge for each of the grades of sediment tested. Although the scatter is great the range of charge is such that a reasonable line can be fitted to the points.

The accuracy of this relation will depend upon the accuracy

with which F_{bo} is known. For the Gilbert and Straub data Lacey's rule was used in estimating F_{bo}. While its limitations are severe (Ref. 1), it should describe F_{bo} quite well for the material used in the Straub tests and for the finer grades of sand used in the Gilbert-Murphy experiment. For coarse material Lacey's rule probably over-estimates the value of F_{bo}.

For the analysis of the data from the experiments of the U.S. Corps of Engineers the values of F_{bo} used were those obtained by extrapolation from plots of F_b versus charge. This method resulted in values of the zero bed factor about twice those which would have been indicated by Lacey's rule, but this will not change the form of $f(C)$ provided the measured bed factor is twice the regime value. This situation could occur if, in view of the very short runs made, the depth had reached only 75% of its regime value, (bed factor depending on the cube of the depth). This, of course, assumes that depth was measured exactly which is unlikely in view of the method employed whereby, before measurements were made, the flume was flooded to give the water surface the same slope as the bed.

As Blench has pointed out (Ref. 9), the King equation for regime slope is so physically meaningful that it seems only reasonable to retain it in form and modify the coefficient. The test equation is then

$$V^2/gdS = K_o\ (1 + f_3(C,D))\ (Vb/\nu)^{1/4} \qquad ....(5.3)$$

in which K_o is the canal value 3.63. The analysis involved the computation of $K = K_o(1 + f_3)$ which was then plotted against charge. Again the scatter is great, but a general relationship is indicated.

Results

Zero Bed Factor

The values of zero bed factor for the Gilbert sediments were not well defined by plots of bed factor against charge. The reason for this was that Gilbert used very large sediment charges and, therefore, in view of the scatter, the evaluation of zero bed factor required too long an extrapolation to be significant. Accordingly, it was necessary to use Lacey's rule to estimate F_{bo}. This same difficulty was encountered with the Straub data. Nor is any useful indication given by the experiments of the Corps of Engineers. Although small charges were used and a value of F_{bo} could be found by extrapolation, such values were twice the correct order as previously mentioned. Thus, pending further experimentation, Lacey's rule remains the only method of estimating F_{bo} from the sediment characteristics.

The Relation of Bed Factor to its Causes

The variation of bed factor with charge for a number of grades of sediment is shown in Figure 3. The plotted points from which these lines were derived are shown in Figures 6 to 18 in Appendix II. The relation between bed factor and its causes can be expressed as

$$F_b = F_{bo} (1 + AC^n) \qquad ....(5.4)$$

in which A and n are functions of the sediment size. For particles up to one millimeter median diameter the index, n, is 5/6 in the relation. One grade of sediment, of median diameter 1.71 mm. follows a two-thirds power law. And for particles of larger size, indices of

one-half and five-twelfths fit the points equally well. All this appears to indicate different relationships for sand and gravel. These relationships are given in Figure 4.

The Modified Slope Formula

The preliminary analysis by Blench (Ref. 9) indicates that, for a dune configuration of the bed, King's coefficient should increase linearly with charge up to some critical value. Further, the value of K_o was taken as 3.63, a value found from observations on canals. Accordingly, the curves fitted to the points shown in Figures 19 to 27 were started at $K_o = 3.63$ and were increased linearly with charge up to, approximately, the critical values given in reference 9. Above this critical value there was no apparent variation of K with charge.

Smooth curves were fitted to the points since, as the King equation is a generalization of the Blasius equation for smooth pipes, it may be reasonable to expect that a modification of the equation to include charge might result in a generalized Moody diagram.

In Figure 5 the smoothing lines of the plots of Figures 19 to 27 are shown. In the sub-critical range K is a function of the charge alone, the function being given by

$$K = 1 + C/M \qquad \ldots\ldots(5.5)$$

with $M = 325$, which agrees fairly well with the value 400 initially proposed by Blench (Ref. 9). For flow near the critical, King's coefficient is a function of both the charge and sediment size and, apparently, a function of sediment size alone for flow in the super-critical range.

Since most natural channels carry only a small charge it is essential to be able to predict K for such cases and equation (5.5) enables this to be done. For flow in the transition and super-critical ranges the value of K could be estimated from Figure 5, but the scatter of the points from which these lines were derived should be kept in mind when applying such values.

Two equations have been derived: One of these describes bed factor in terms of the sediment characteristics and charge and appears to be valid for all values of charge. The other generalizes the King equation for slope and is valid for low charges only.

It should be noted that the concept of a bed factor at zero charge may not be rigorously correct. That is, the movement of bed material may depend upon probability considerations and be possible at any stage of flow. As Blench points out (Ref. 24) the dividing line between bed movement and no bed movement may be similar to that between laminar and turbulent flow. However, it seems reasonable to believe (Ref. 18) that there is at least an asymptotic value which bed factor approaches as the charge is diminished.

At present it seems impossible to attach any dynamical meaning to the equation describing bed factor. It is simply necessary that it depend upon charge and sediment characteristics, and for vanishingly small values of charge reduce to a function of sediment properties alone.

It should also be noted that K, which is independent of charge for high values of charge, is the ratio of V^2/gdS, a measure of the bed friction, to $(Vb/\nu)^{1/4}$, a measure of the side friction. Why this quantity should be independent of charge for super-critical flow is not clear.

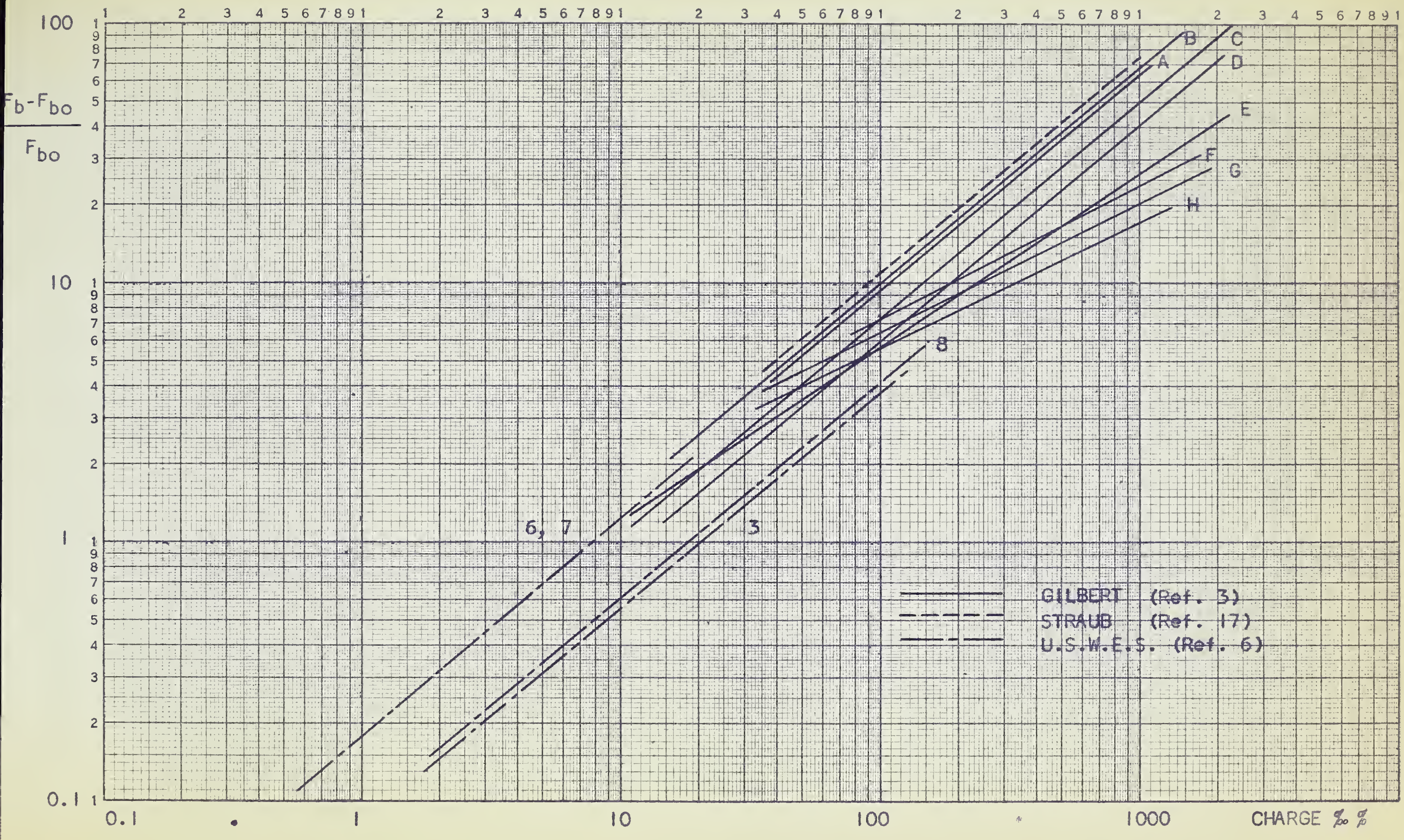


FIGURE 3. TEST OF $F_b = F_{bo}(1 + AC^n)$

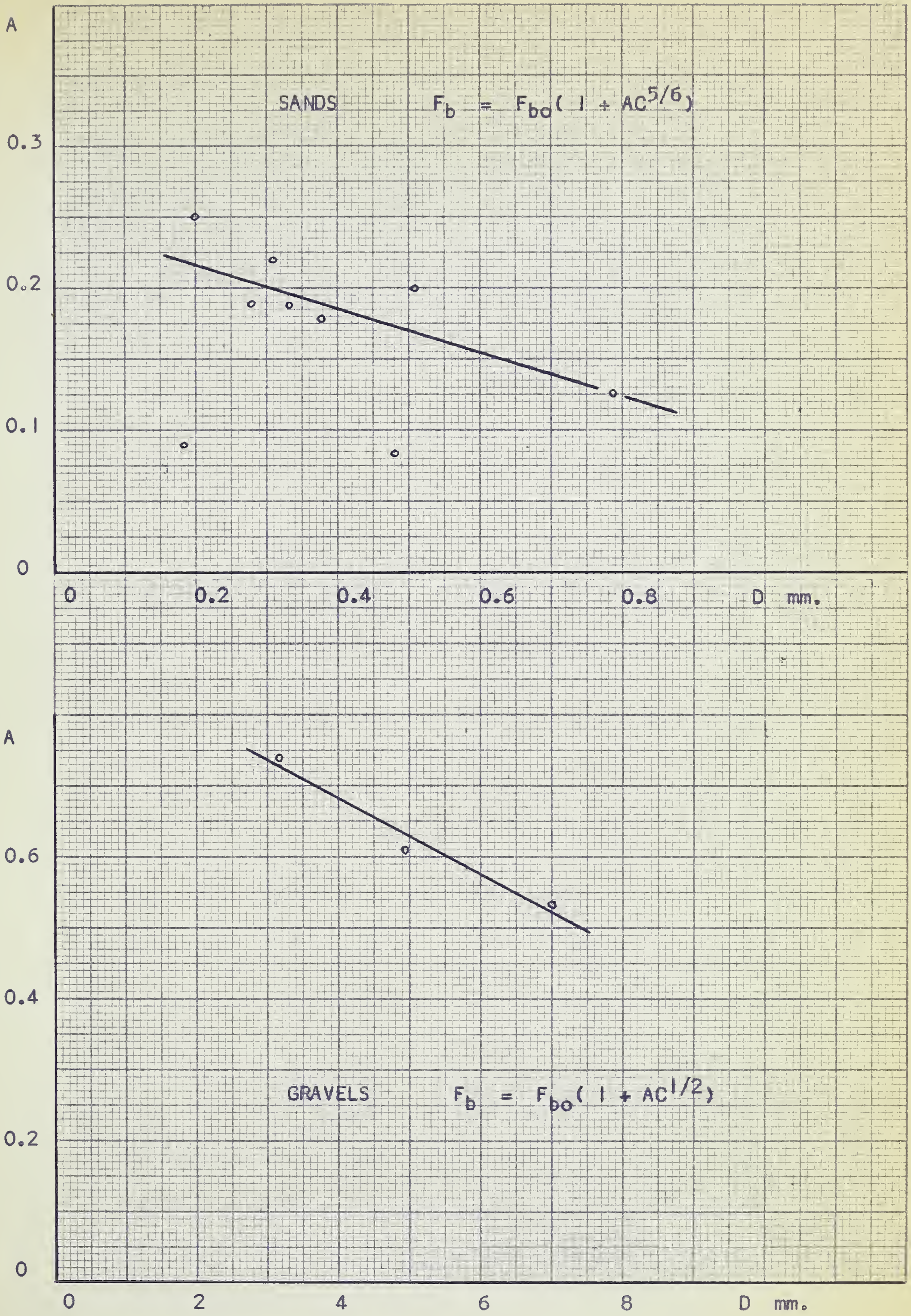
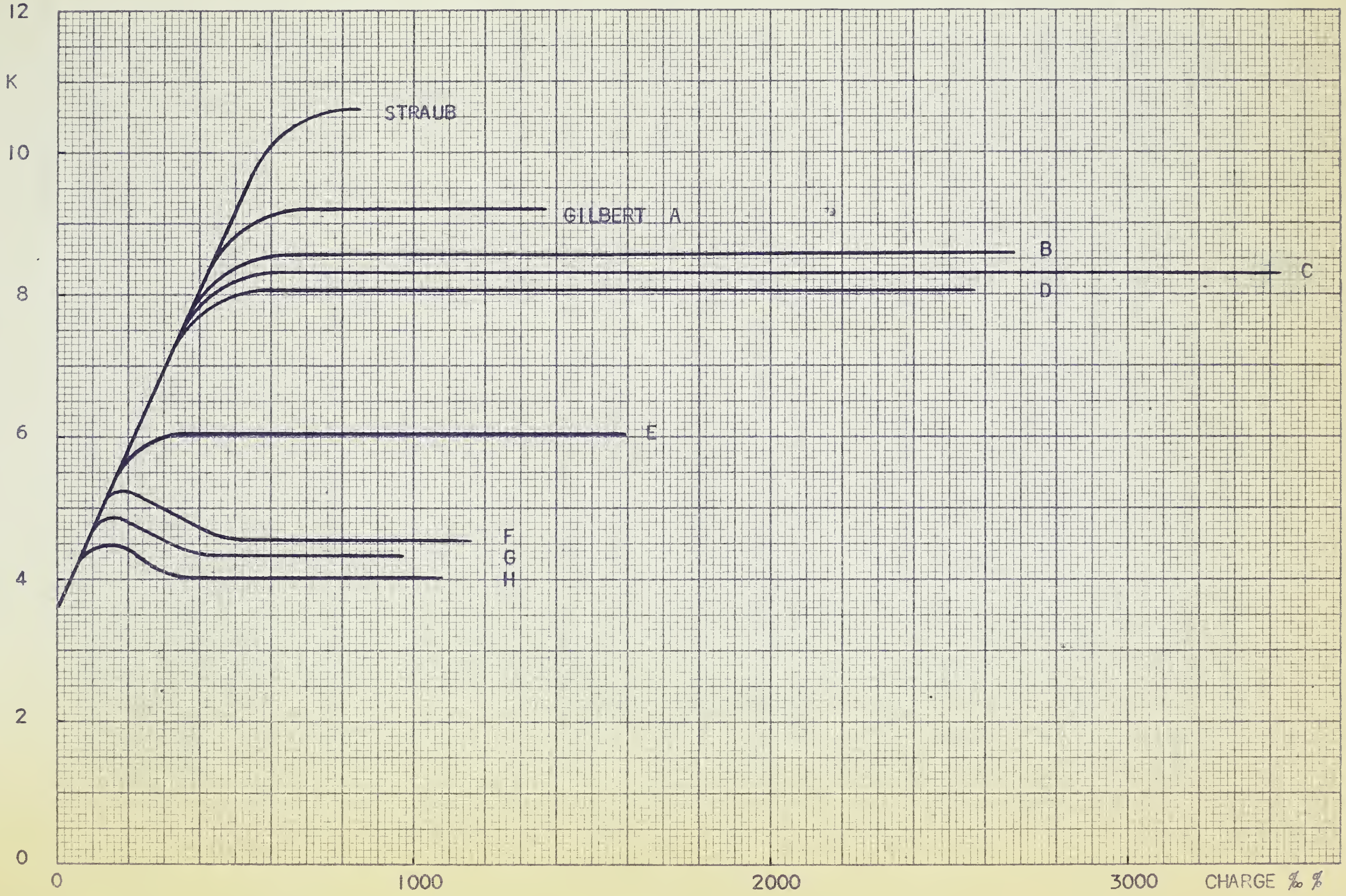


FIGURE 4. VALUES OF 'A' IN THE BED FACTOR EQUATION

FIGURE 5. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE



Suspended Load

In view of the success of analyzing bed load transport by regime methods a similar approach was used to consider suspended load transport.

There were two sources of data. A series of experiments by Vanoni (Ref. 26) gave data covering three grades of sand, two values of slope and a series of discharges for one flume width. Also, in one of the experiments of the U.S. Corps of Engineers (Ref. 6) suspended load measurements were taken and these data were used as well.

Unfortunately the results of these two studies can not be combined since the Vanoni experiments were performed with a rigid boundary, and those of the Corps of Engineers were for regime boundary conditions.

For the Vanoni data an attempt was made to correlate the absolute rugosity, x, with suspended load charge. From the Blench general flow formula (Ref. 28)

$$V^2/gdS = 20.4\ (d/x)^{1/2}$$

$$x^{1/4} = 25.6\ \frac{d^{3/4}S^{1/2}}{V}$$

The quantity $x^{1/4}$ is plotted against suspended load charge in Figure 28.

A well known feature of canals is the apparent change of viscosity of the water with suspended load. Accordingly an attempt was made to correlate with suspended load charge the viscosity, as determined by the modified King equation, that is, corrected for bed load transport.

$$\nu = (3.63\ g)^4 (1 + C/325)^4 (dS/V)^4 / F_s$$

In Figure 29, $\nu^{1/4}$ is plotted against suspended load charge.

When complete data are available a regime analysis will probably describe adequately the effect of suspended load on channel geometry, but at present no conclusions can be drawn.

6. A Comparison of Methods of Describing Sediment Transport

The conventional approach to the study of sediment transport has been from flume experiments. Formulas are derived to describe the results of the experiments and then applied to rivers under natural conditions.

The approach adopted by Blench (Ref. 9) and used in the present study starts with the regime formulas, which were derived from observations on canals and found to apply to rivers, and extends them to include the results of flume studies on both uniform and graded material. This extension yields sediment transport relations in the form of modified regime formulas which should give useful indications when applied to canals and rivers.

Critical Tractive Force Methods (Ref. 5)

These methods are based on the assumption that at some 'critical' stage the tractive force of the flowing water will begin to move bed material. Most of the critical tractive force formulas can be expressed as

$$q_B \ \alpha \ (T - T_c)^m$$

in which q_B is the rate of transport of bed-load per unit width of bed, T the tractive force, m a function of the sediment in transport and the subscript c refers to 'critical' conditions.

Such formulas are hard to justify on theoretical grounds (Ref. 1) but they have been widely used because they are easy to apply and describe fairly well the transport of sediment for the very limited range of conditions prevailing in flume experiments.

The Einstein Bed-Load Function (Ref. 12)

This method describes the mechanisms of sediment transport from the microscopic point of view of the individual particles. Bed movement is described in terms of probability functions and flume data are used to evaluate the constants. The result is the relation

$$1 - \frac{1}{\sqrt{\pi}} \int_{-B_* \psi - 1/\eta_o}^{B_* \psi - 1/\eta_o} e^{-t^2} dt = \frac{A_* \phi}{1 + A_* \phi}$$

in which ψ is a measure of the flow intensity, ϕ the intensity of bed-load transport and A_*, B_* and η_o are universal constants. The method is complex and the results difficult to apply but it describes adequately the transport of sediment at low discharge intensities and has the advantage of including the density of the material. However, its application to large scale channels such as canals and rivers is dangerous (Ref. 29), because the data on which the theory is based were derived for only a very limited range of conditions.

The Meyer-Peter Method (Ref. 4)

This method presents an empirical formula connecting rate of transport with particle size and slope. Its basis is mainly in flume experiments on uniform material. The original equation was

$$\frac{q^{2/3} S}{D} = a + b \frac{q_B{}^{2/3}}{D}$$

in which q is the discharge intensity and a and b are constants. This equation has since been modified to the extent of raising S as well as q to the two-thirds power.

This method is easy to apply and works particularly well for the transport of large material along steep slopes. Since it fails to describe the transport of material finer than 1 mm. (Ref. 30) it cannot be used for canals and sand bed rivers, but is useful in such applications as rock rapids.

The Regime Theory Approach

This method extends the basic formulas which describe canals to include the transport of sediment. The formulas are empirical; nevertheless are dynamically sound and apply over a very large range of conditions. The method is simple and easy to apply and has the advantage of using the basic data of flume experiments. The results may be written as in equations (5.4) and (5.5). Since the basic equations apply to canals and rivers transporting a vanishingly small charge, the modified equations should indicate the behavior of channels carrying a finite charge. Equation (5.4) appears to hold well above the sub-critical range.

So far no method has been found of including the effects of the suspended load or of particle density. Also the application of the results to gravel is doubtful because of the lack of data for particles of median diameter greater than seven millimeters.

7. A Suggested Programme for Future Research

For the rational design and control of alluvial channels the present state of laboratory knowledge is hopelessly inadequate. Further, this situation can be rectified only by extensive research and not by further manipulation of the existing data. Although the main need is for experimental work, there are lines along which theoretical investigations could profitably proceed.

Experimental Programme

It is essential that complete experiments be carried out to:

(a) Determine the dependence of F_{bo} on sediment characteristics.
(b) Verify equation (5.4) and determine accurately the values of the coefficients.
(c) Determine the possible variation of K_o with the sediment characteristics.
(d) Determine exactly the modified form of King's coefficient.
(e) Investigate the possible effect of width to depth ratio and, for super-critical flow, the ratio of depth to particle size.

These investigations should include uniform and naturally graded material ranging in size from 0.1 mm. to at least one foot in diameter. Since nothing is known about change of regime long flumes will be necessary in order to eliminate the entrance and exit effects and give a reach over which slope can be accurately measured. As Blench (Ref. 9) has pointed out "..this apparently simple task will call for vast cooperative effort".

Investigation of Sediment Characteristics

The separate topic of sediment characteristics deserves careful study. In the present study the case for sands has been considered only briefly and that for gravel not at all.

A wealth of material exists in the field of geology and it is felt that from a study of this material much information could be obtained which would be of interest to river engineers. In addition an experimental programme would be desirable, with particular attention given to size, shape, density and grading.

Additional Studies

Other topics which should be studied are the mode of formation of dunes, density currents as mechanisms of sediment transport and suspended load. Particularly the subject of suspended load should receive attention, and this would involve as well a study of the mechanisms of turbulence.

8. Summary

1. For natural sands a relation has been found between the median grain size and the distribution of particles about the median. This enables the characteristics of such a sand to be described by a single measure.

2. A regime analysis of flume data on sediment transport has been found to work as well as any previous method, and has the advantage of handling the data untreated.

3. Modifications to the regime formulas have been proposed:

   (a) $F_b = F_{bo} (1 + AC^n)$ which relates bed factor to the nature and quantity of the transported material.

   (b) $V^2/gdS = K_o (1 + C/325)(Vb/\nu)^{1/4}$ which generalizes the slope equation to include charge and can be easily used to determine sediment load if slope is known.

4. The relations stated in 3. are only approximate because of the lack of data, and the great scatter in such data as exist. In particular the relation giving zero bed factor as a function of sediment characteristics is of little value for large sizes of sediment.

5. An extensive research programme is essential if our understanding of sediment transport is to be improved.

BIBLIOGRAPHY

1. Blench, Thomas, Hydraulics of Sediment-Bearing Canals and Rivers; Evans Industries Limited, Vancouver, B.C., Canada, 1951.

2. Inglis, Sir C.C., Historical Note on Empirical Equations, developed by Engineers in India for Flow of Water and Sand in Alluvial Channels; Proc. International Association for Hydraulic Structures Research, 1948.

3. Gilbert, Grove Karl, The Transportation of Debris by Running Water; Based on experiments made with the assistance of Edward Charles Murphy; U.S. Geological Survey, Professional Paper 86.

4. Meyer-Peter, E. and Muller, R., Formulas for Bed-Load Transport; Proc. International Association for Hydraulic Structures Research, 1948.

5. Chien, Ning, The Present Status of Research on Sediment Transport; Proc. A.S.C.E., Separate No. 565, December 1954.

6. Corps of Engineers, U.S. Army, Studies of River Bed Materials and Their Movement, with Special Reference to the Lower Mississippi River; Paper 17 of the U.S. Waterways Experiment Station, Vicksburg, Mississippi, January, 1935.

7. Evans, O.F., Transportation of Sediments on Fresh-Water Surfaces by Flotation; Journal of Sedimentary Petrology, Vol. 8, No. 1, pp. 33-35, April, 1938.

8. Danel, P., Durand, R. and Condolois, E., Introduction a l'Etude de la Saltation; La Houille Blanche, December, 1953.

9. Blench, Thomas, Regime Formulas for Bed-Load Transport; Submitted to I.A.H.R. for 1955 meeting.

10. Bagnold, R.A., The Transport of Sand by Wind; The Geographical Journal, May, 1937.

11. Subcommittee on Sedimentation Federal Inter-Agency River Basin Committee, A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams, Preliminary Report on Some Fundamentals of Particle Size Analysis; Minneapolis, Minnesota, March, 1954.

12. Einstein, H.A., The Bed-Load Function for Sediment Transportation in Open Channel Flows; Tech. Bull. No. 1026, U.S. Dept. of Agriculture, Soil Conservation Service, Washington, D.C., September, 1950.

13. Krumbein, W.C., Size Frequency Distributions of Sediments and the Normal Phi Curve; Journal of Sedimentary Petrology, Vol. 8, No. 3, pp. 84-90, December, 1938.

14. Otto, George H., A Modified Logarithmic Probability Graph for the Interpretation of Mechanical Analyses of Sediments; Journal of Sedimentary Petrology, Vol. 9, No. 2, pp. 62-76, August, 1939.

15. Blench, Thomas, Normal Size Distributions Found in Samples of River Bed Sand; Civil Engineering, Vol. 22, No. 2, p. 147, 1952.

16. Einstein, H.A., Bed-Load Transportation in Mountain Creek; SCS-TP-55, U.S. Dept. of Agriculture, Soil Conservation Service, Washington, D.C., August, 1944.

17. Straub, Lorenz G., Terminal Report on Transportation Characteristics of Missouri River Sediment; Prepared for the Missouri River Division Corps of Engineers, U.S. Army, Minneapolis, Minnesota, April, 1954.

18. Appelt, V.M., Model Studies of River Control Methods; Thesis submitted as part requirement for the degree of M.Sc. from the University of Alberta, 1955.

19. Peterson, Allan W., The Design, Construction and Use of a River Tray; Thesis submitted as part requirement for the degree of M.Sc. from the University of Alberta, 1954.

20. Harrison, Alfred S., Report on Special Investigation of Bed Sediment Segregation in a Degrading Bed; Series 33, Issue No. 1, University of California, Institute of Engineering Research, Berkeley, California, September, 1950.

21. Pollock, D.H., Air Photo Analysis, Report in preparation; Engineering Geology Division, P.F.R.A., Department of Agriculture, Canada.

22. Subcommittee on Sedimentation Federal Inter-Agency River Basin Committee, A study of Methods Used in Measurement and Analysis of Sediment Loads in Streams, Report No. 4, Methods of Analyzing Sediment Samples; St. Paul District Sub-Office, Hydraulic Laboratory, University of Iowa, Iowa City, Iowa, November, 1941.

23. Krumbein, W.C., and Pettijohn, F.J., Manual of Sedimentary Petrography; D. Appleton - Century Company, New York, 1938.

24. Blench, Thomas, Practical Regime Theory Design of Artificial Channels with Self-Adjustable Boundaries; Submitted, by request, for A.S.C.E. Convention at St. Louis, June, 1955.

25. Blench, Thomas, Regime Theory Equations Applied to a Tidal River Estuary; Proc. I.A.H.R., Joint Convention with A.S.C.E., Minneapolis, September, 1953.

26. Vanoni, Vito A., Transportation of Suspended Sediment by Water; Paper No. 2267, Trans. A.S.C.E., Vol. III, 1946.

27. Blench, Thomas, Note on Studies of Bed-Sand Movement in Flumes; Report to National Reaearch Council, University of British Columbia, September, 1951.

28. Blench, Thomas, The Flow Formula of Practical Hydraulics; Extract from La Houille Blanche, No. 4, August - September, 1952.

29. Blench, Thomas, Comments on A.S.C.E. Proc. Separate 565; (Ref. 5), Submitted to A.S.C.E., March, 1955.

30. Einstein, H.A., Formulas for the Transportation of Bed Load; Paper No. 2140, Trans. A.S.C.E., Vol 107, 1942.

Appendix I

Notation

Sediment Characteristics

V_s	Settling velocity in still water at 20° C.
δ	Dispersion of particles about median grain size.
S_o	Sorting coefficient $= (Q_1/Q_3)^{1/2}$
Q_1, Q_3	Respectively first and third quartile sizes.
D	Size of median grain of a sediment mixture.

Sediment Transport

V	Mean velocity of flow.
d	Mean depth of flow.
b	Breadth of channel.
P	Wetted perimeter of channel.
R	Hydraulic radius of channel.
g	Acceleration of gravity.
f	Lacey's silt factor.
S	Channel slope, bed and water surfaces assumed parallel.
ν	Kinematic viscosity.
ρ	Density of water.
F_b	A bed factor defined by V^2/d.
F_s	A side factor defined by V^3/b.
Q	Total discharge through channel.
q	Discharge per unit breadth of channel.
C	Bed-sediment charge, defined as weight of bed-load sediment per second divided by weight of water per second, expressed in thousandths of one percent.

K	King's coefficient in regime equation for slope.
M	Defined in equation (5.5).
x	Rugosity of a rough rigid boundary.
A, n, m	Functions of sediment characteristics.
q_B	Rate of transport of sediment per unit width of channel.
T	Tractive force on channel bed.
ϕ	Intensity of bed-load transport defined by $\frac{q_B}{\rho_s g}\left(\frac{\rho_f}{\rho_s-\rho_f}\right)^{1/2}\left(\frac{1}{gD^3}\right)^{1/2}$
ψ	Intensity of flow defined by $\frac{\rho_s-\rho_f}{\rho_f}\,\frac{D}{R_b'S}$
A_*	Universal constant = 43.5
B_*	Universal constant = 0.413
η	Universal constant = 1/2
R_b'	Hydraulic radius of grain resistance.

Subscripts

c	Critical conditions, i.e. start of bed movement.
0	Conditions at vanishingly small charge.
s	Suspended
f,s	When with ρ, respectively fluid and sediment density.
60,10	With D, size for which the aggregate weight for all smaller grains is 60%, 10% of the total weight.

APPENDIX II

FIGURES 6 to 29

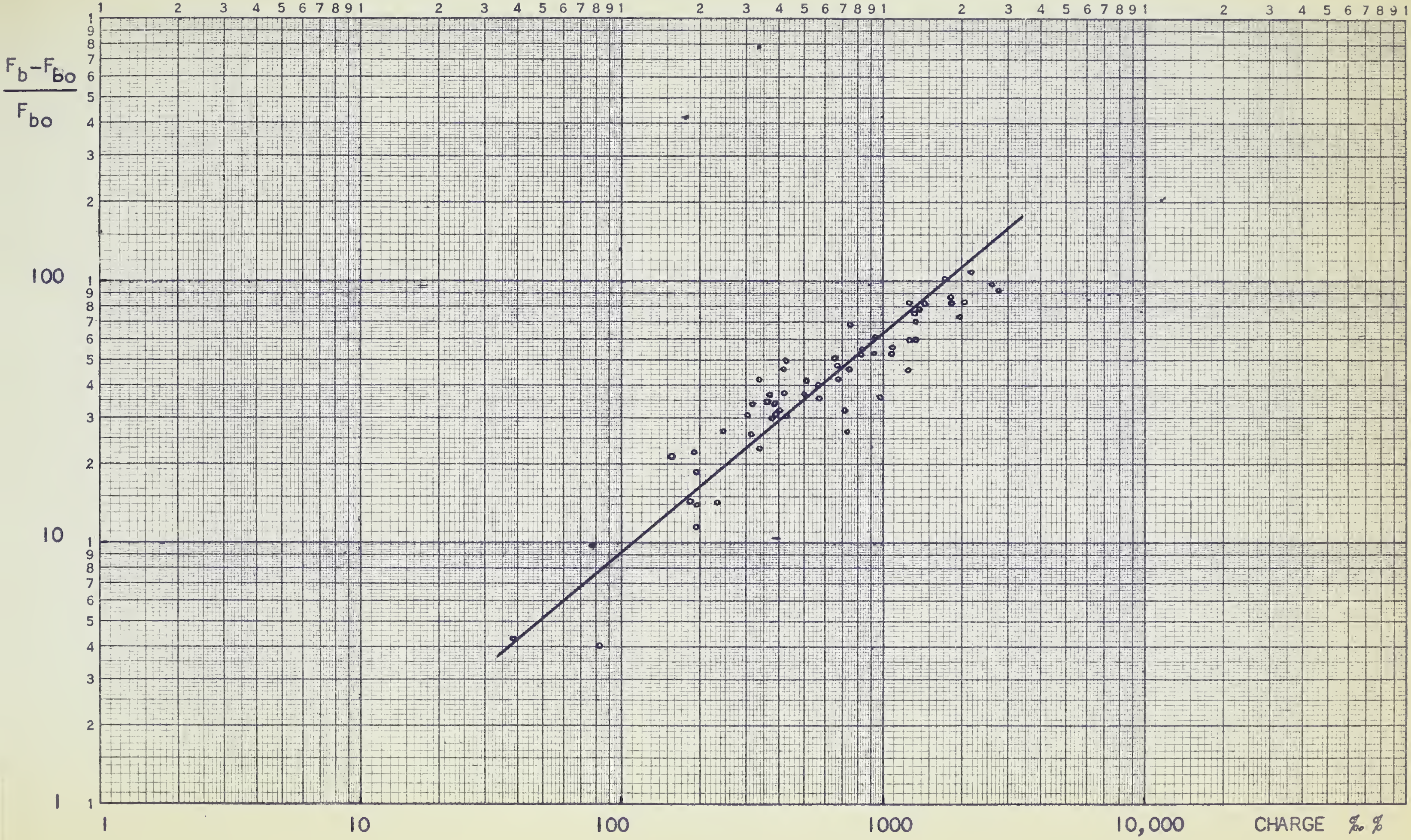


FIGURE 6. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR GILBERT SAND 'A', $D = 0.305$ mm.

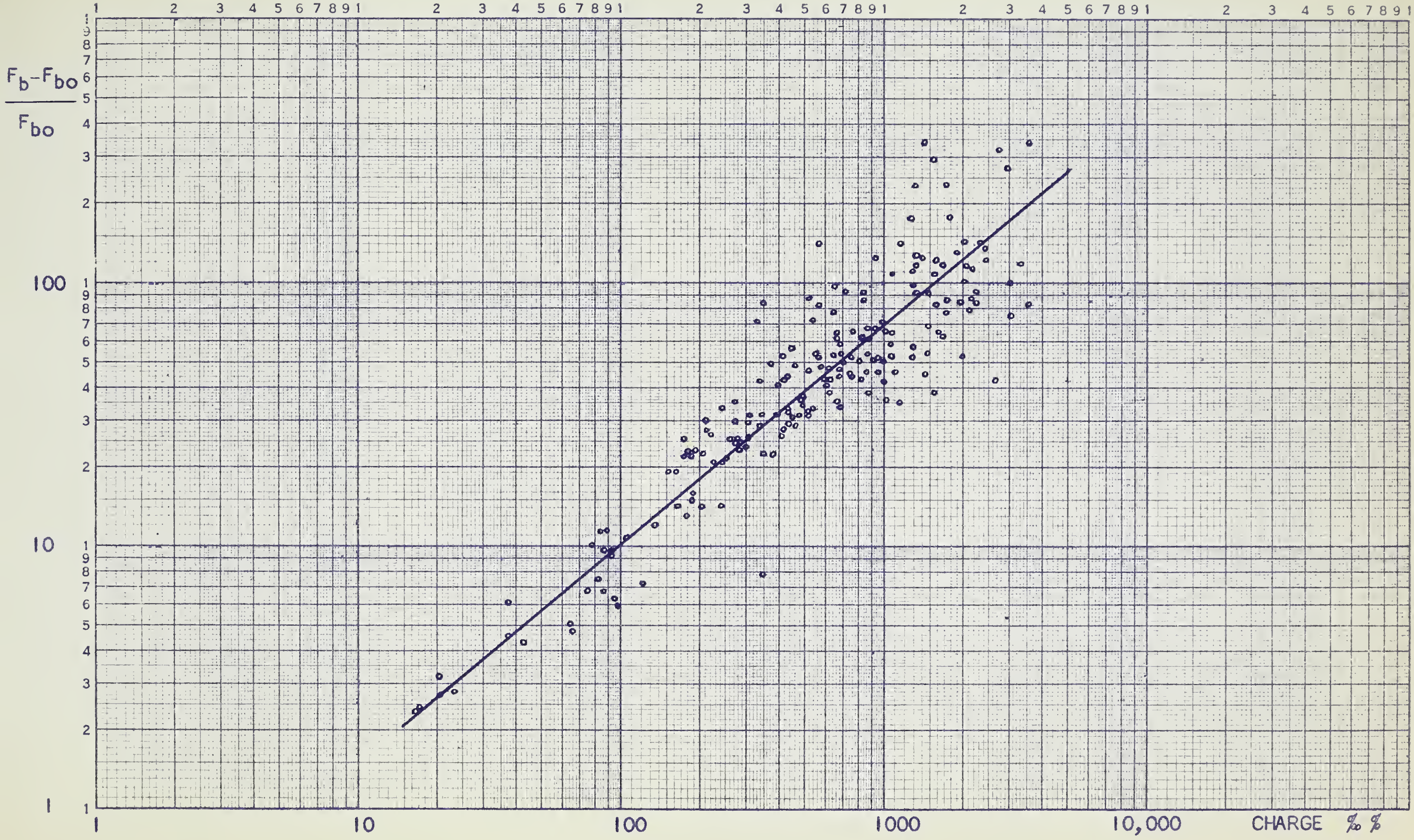


FIGURE 7. TEST OF $F_b = F_{bo} (1 + AC^n)$ FOR GILBERT SAND 'B', D = 0.374 mm.

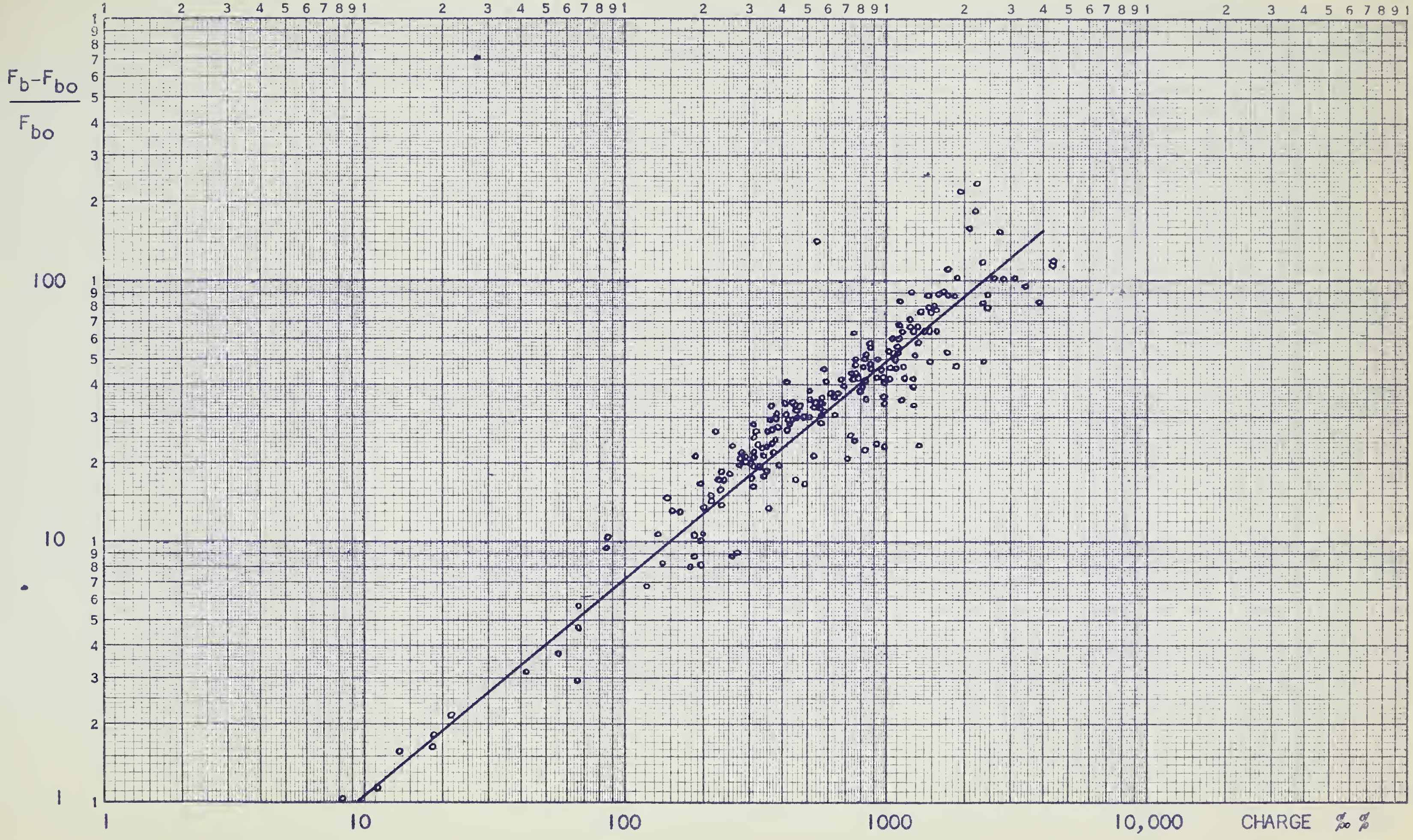


FIGURE 8. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR GILBERT SAND 'C' D = 0.506 mm.

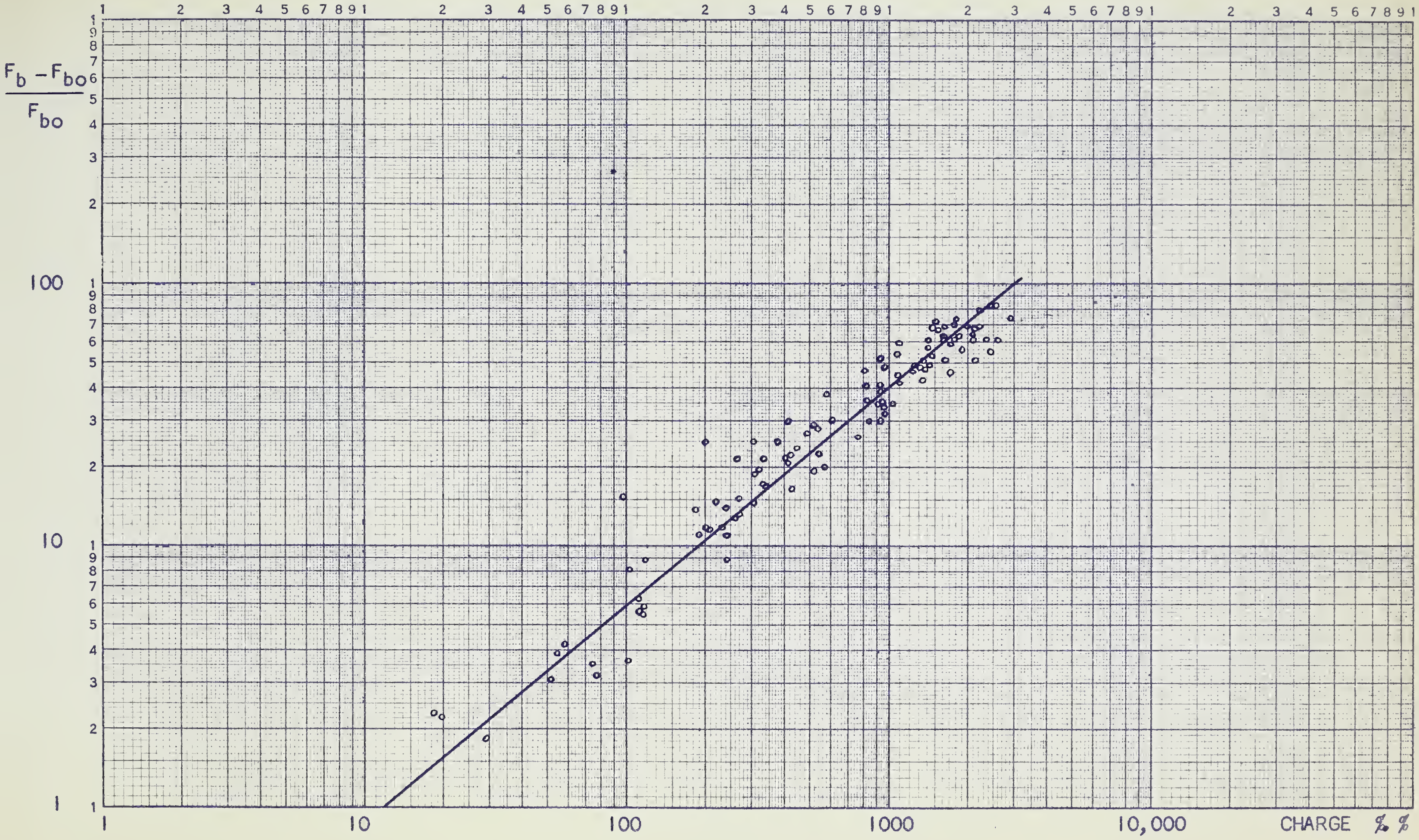


FIGURE 9. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR GILBERT SAND 'D', D = 0.786 mm.

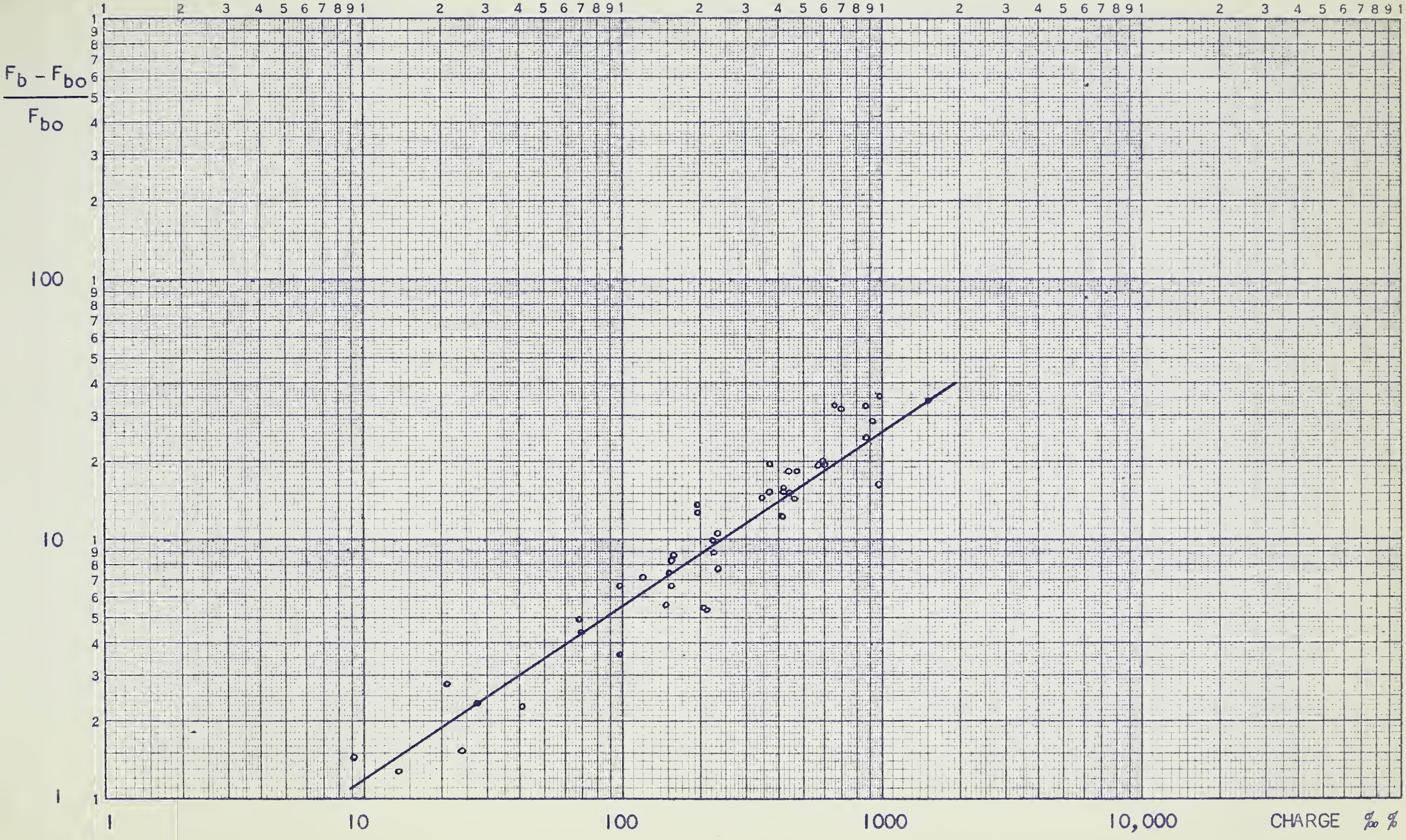


FIGURE 10. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR GILBERT SAND 'E', D = 1.71 mm.

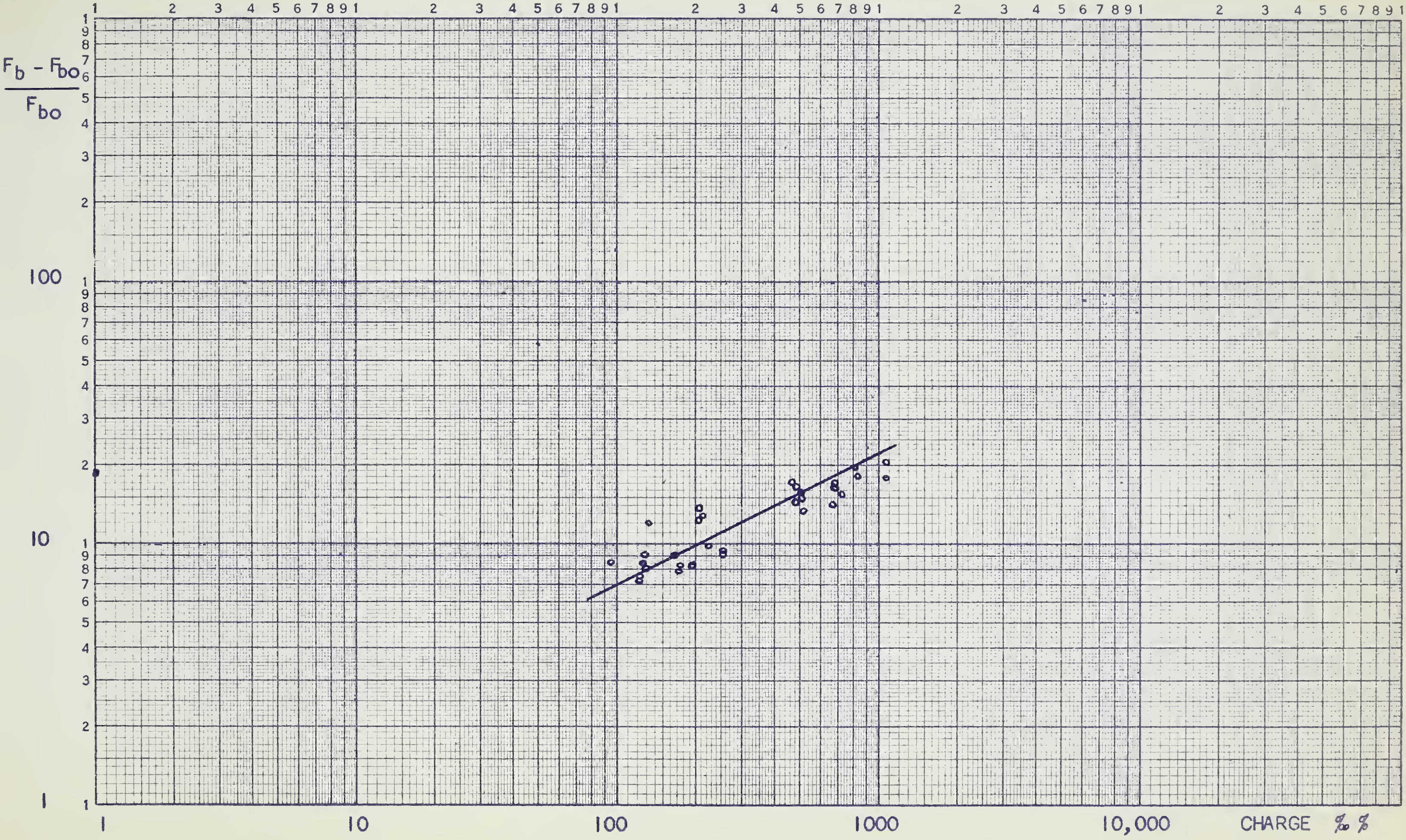


FIGURE 11. TEST OF $F_b = F_{bo} (1 + AC^n)$ FOR GILBERT SAND 'F', D = 3.17 mm.

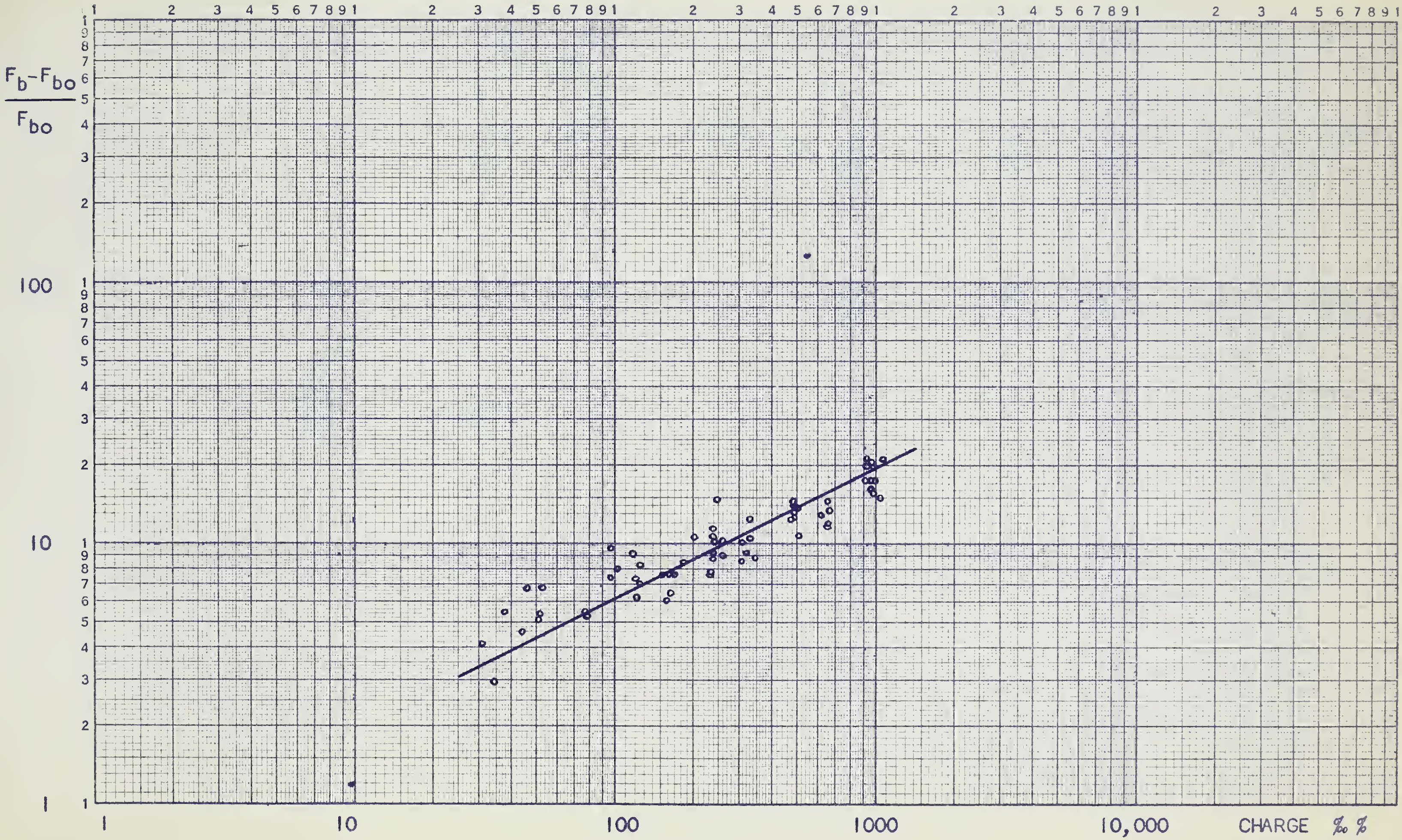


FIGURE 12. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR GILBERT SAND 'G', D = 4.94 mm.

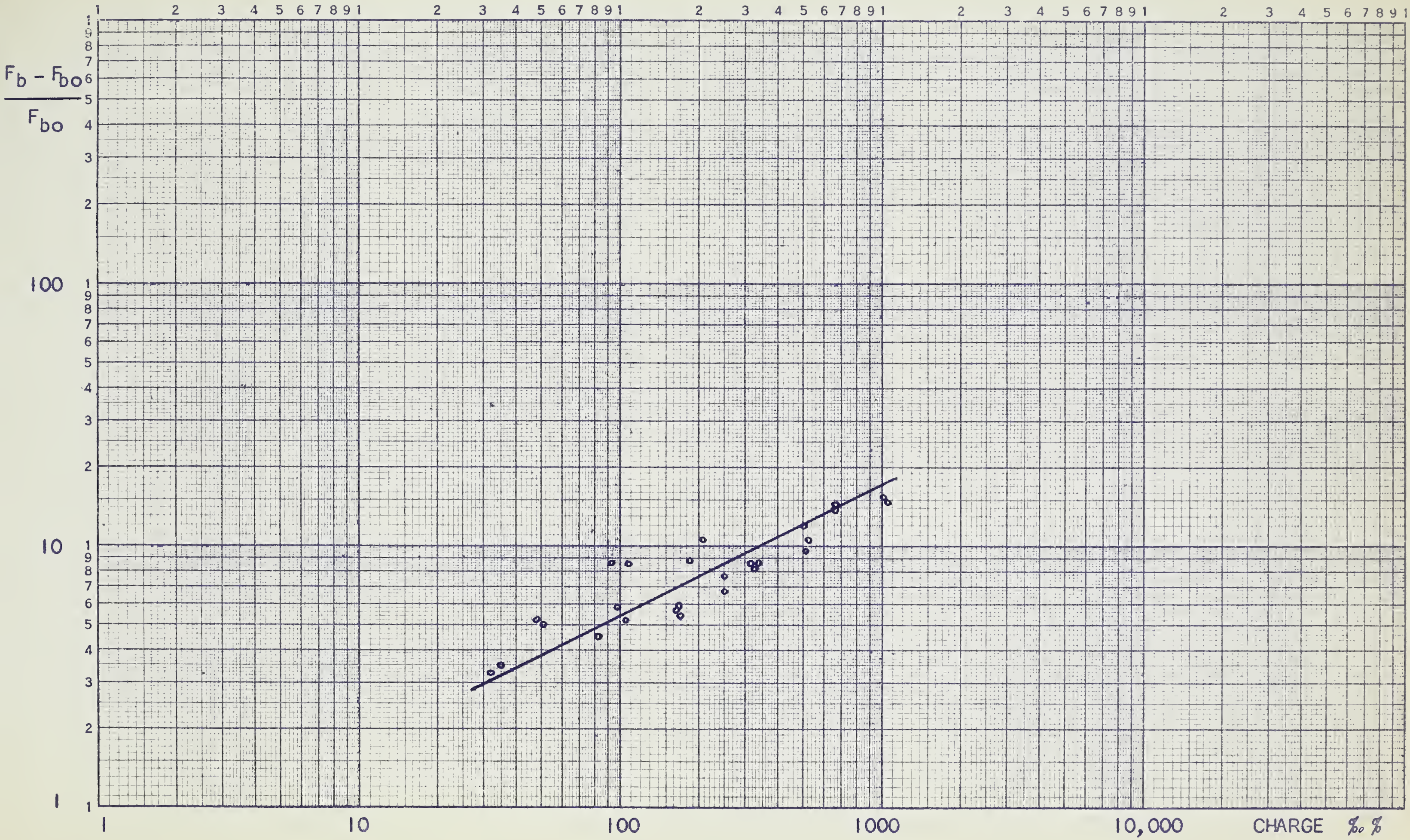


FIGURE 13. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR GILBERT SAND 'H', D = 7.00 mm.

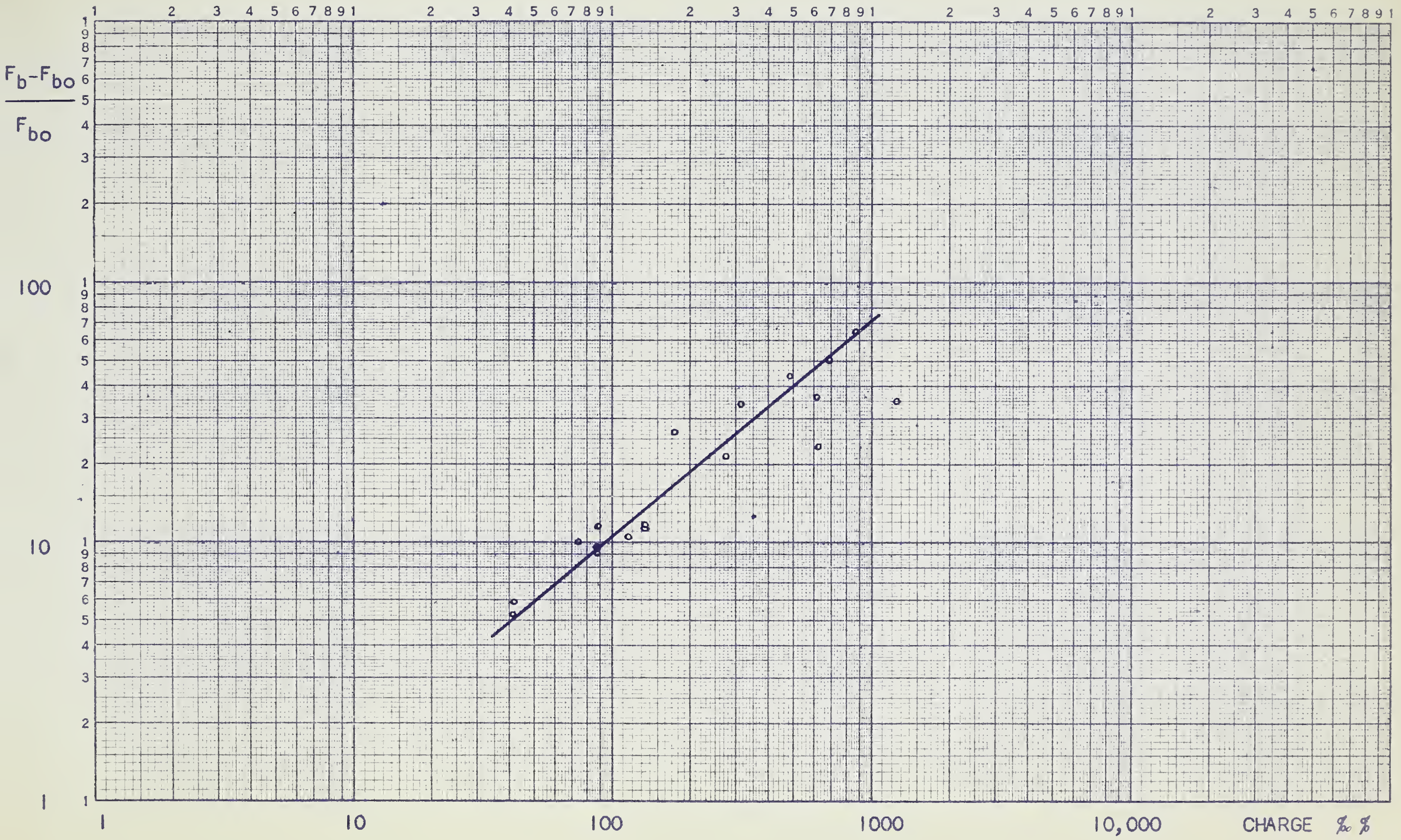


FIGURE 14. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR STRAUB SEDIMENT; D = 0.185 mm.

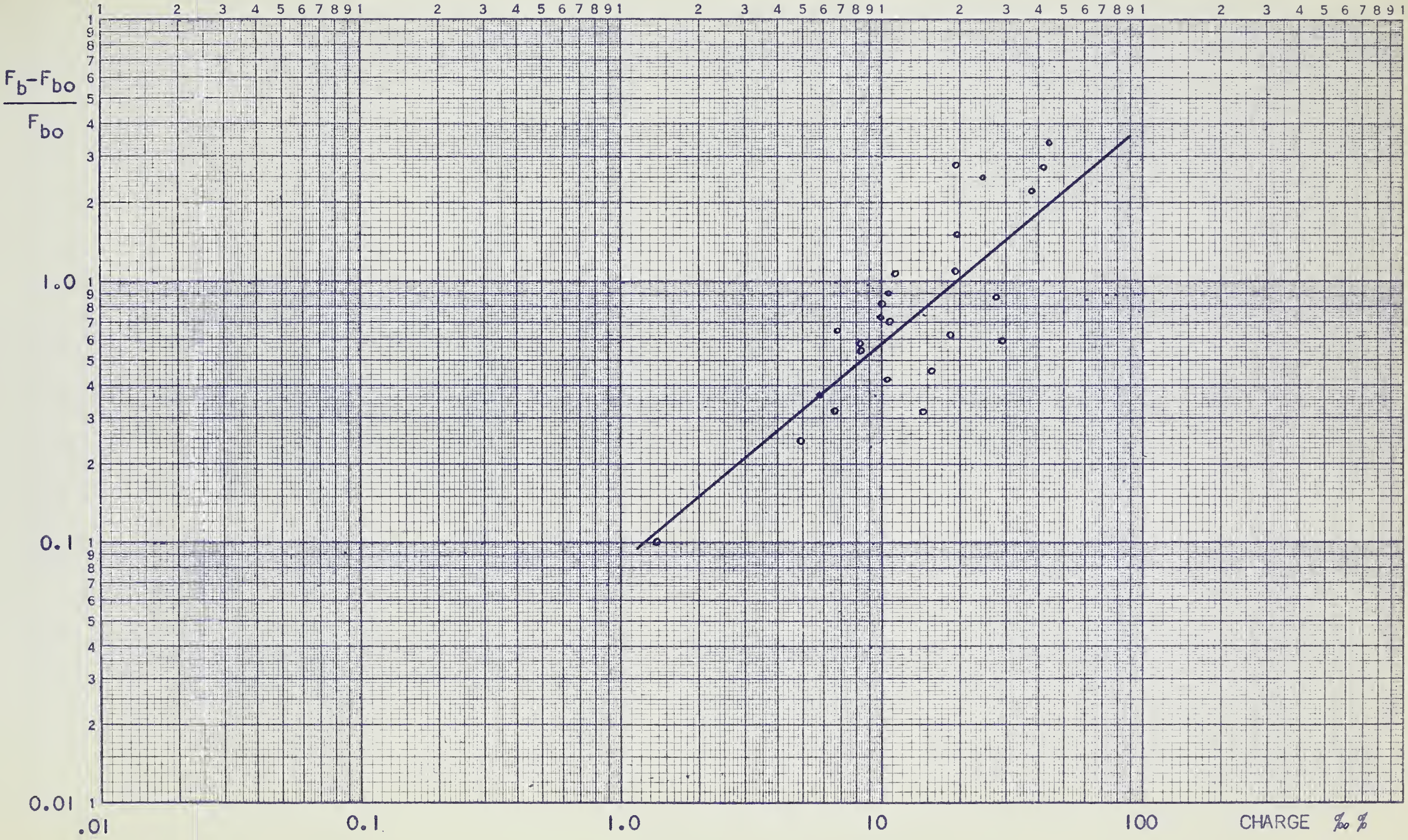


FIGURE 15. TEST OF $F_b = F_{bo} (1 + AC^n)$ FOR U.S.W.E.S. PAPER 17 SAND No. 3, D = 0.48 mm.

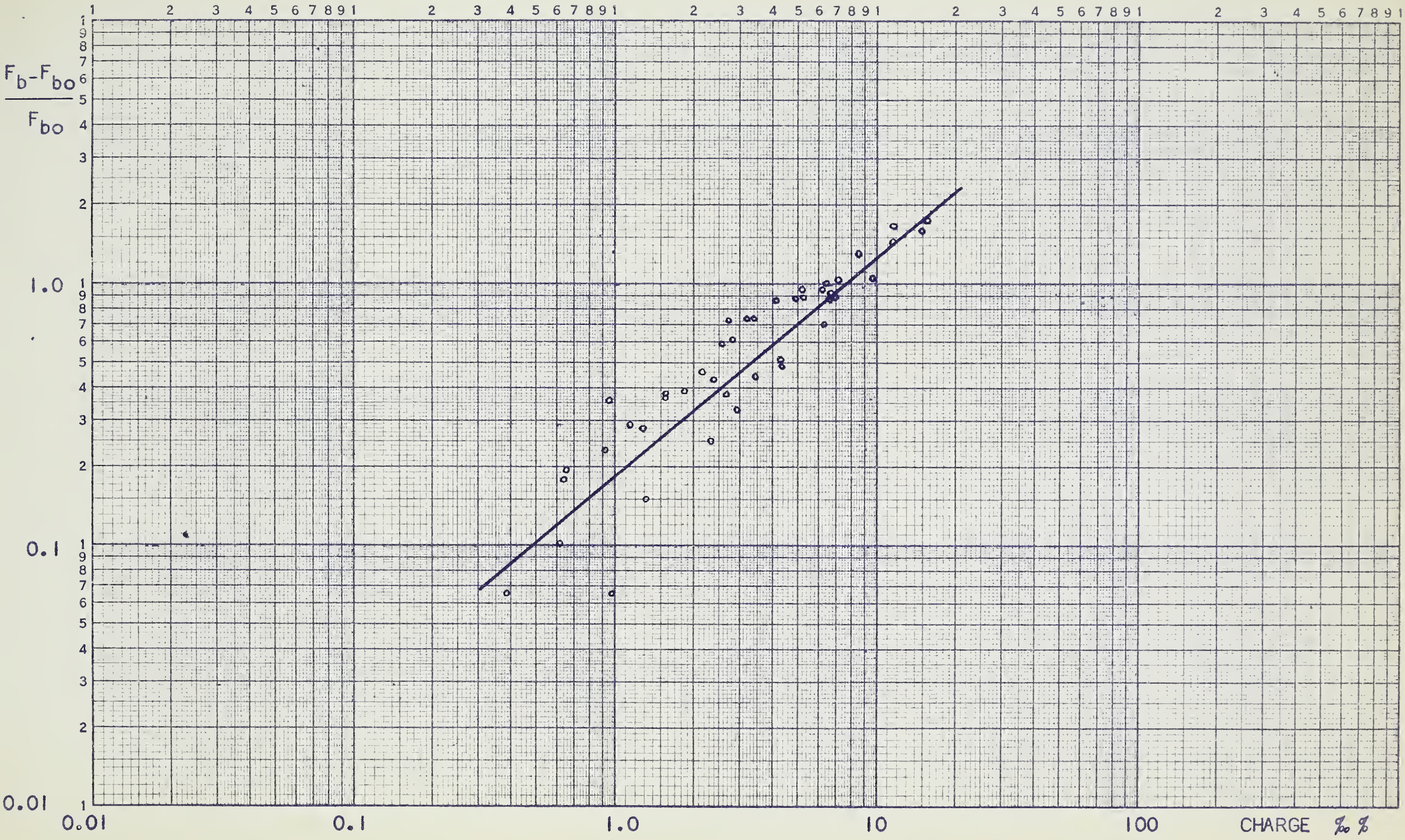


FIGURE 16. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR U.S.W.E.S. PAPER 17 SAND No. 6, D = 0.33 mm.

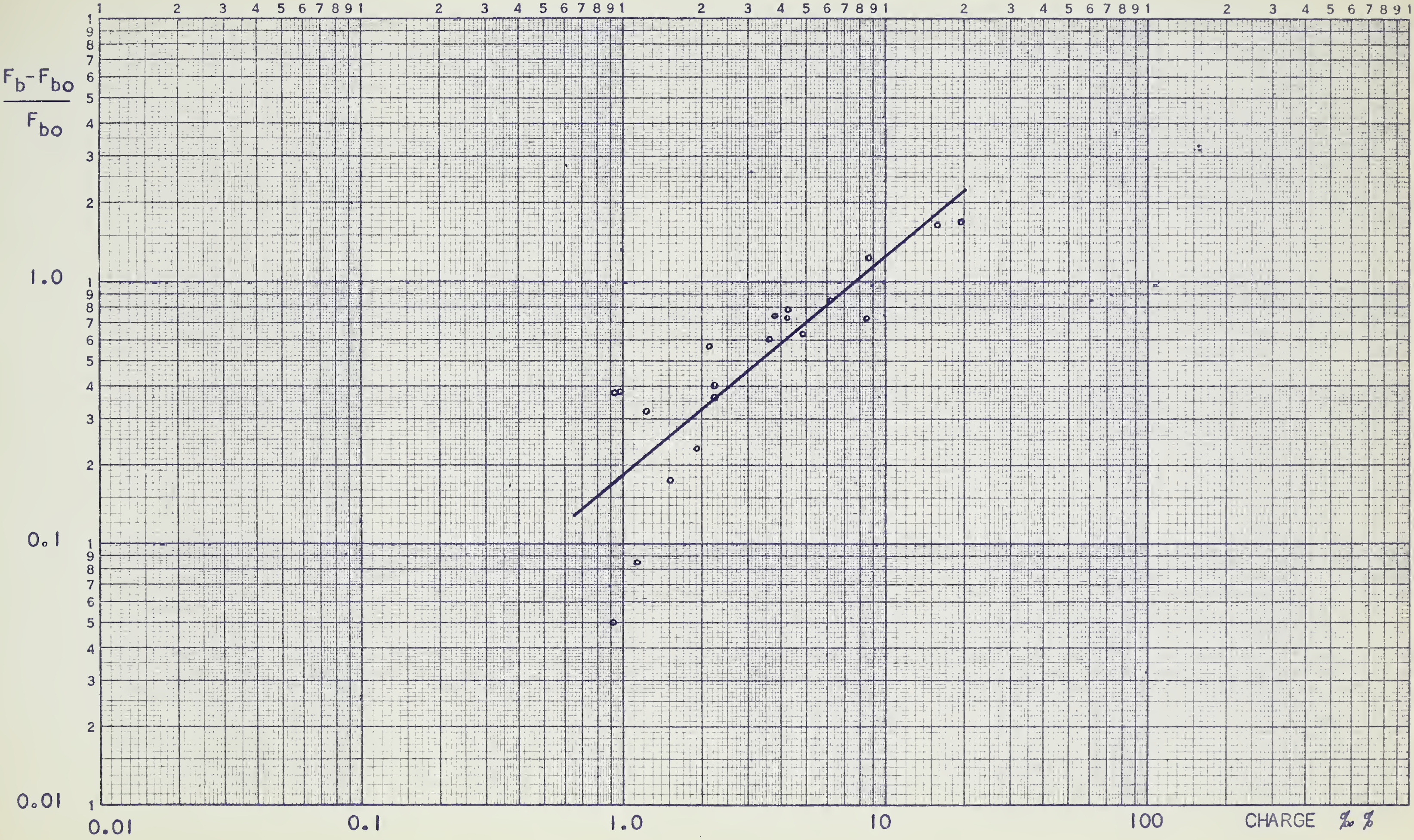


FIGURE 17. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR U.S.W.E.S. PAPER 17 SAND No. 7, D = 0.28 mm.

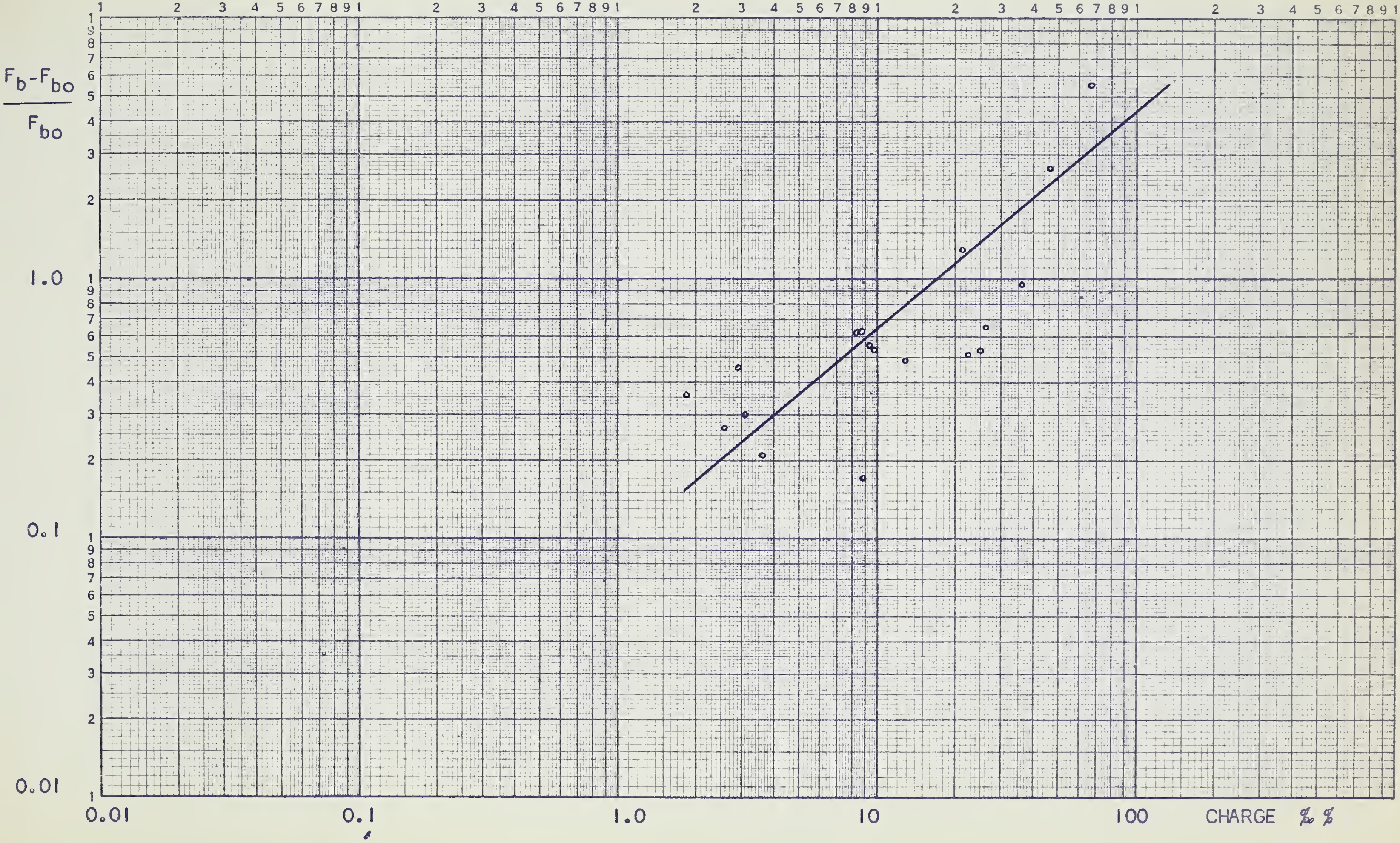


FIGURE 18. TEST OF $F_b = F_{bo}(1 + AC^n)$ FOR U.S.W.E.S. PAPER 17 SAND No. 8, D = 0.18 mm.

FIGURE 19. VARIATION OF KINGS COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'A'

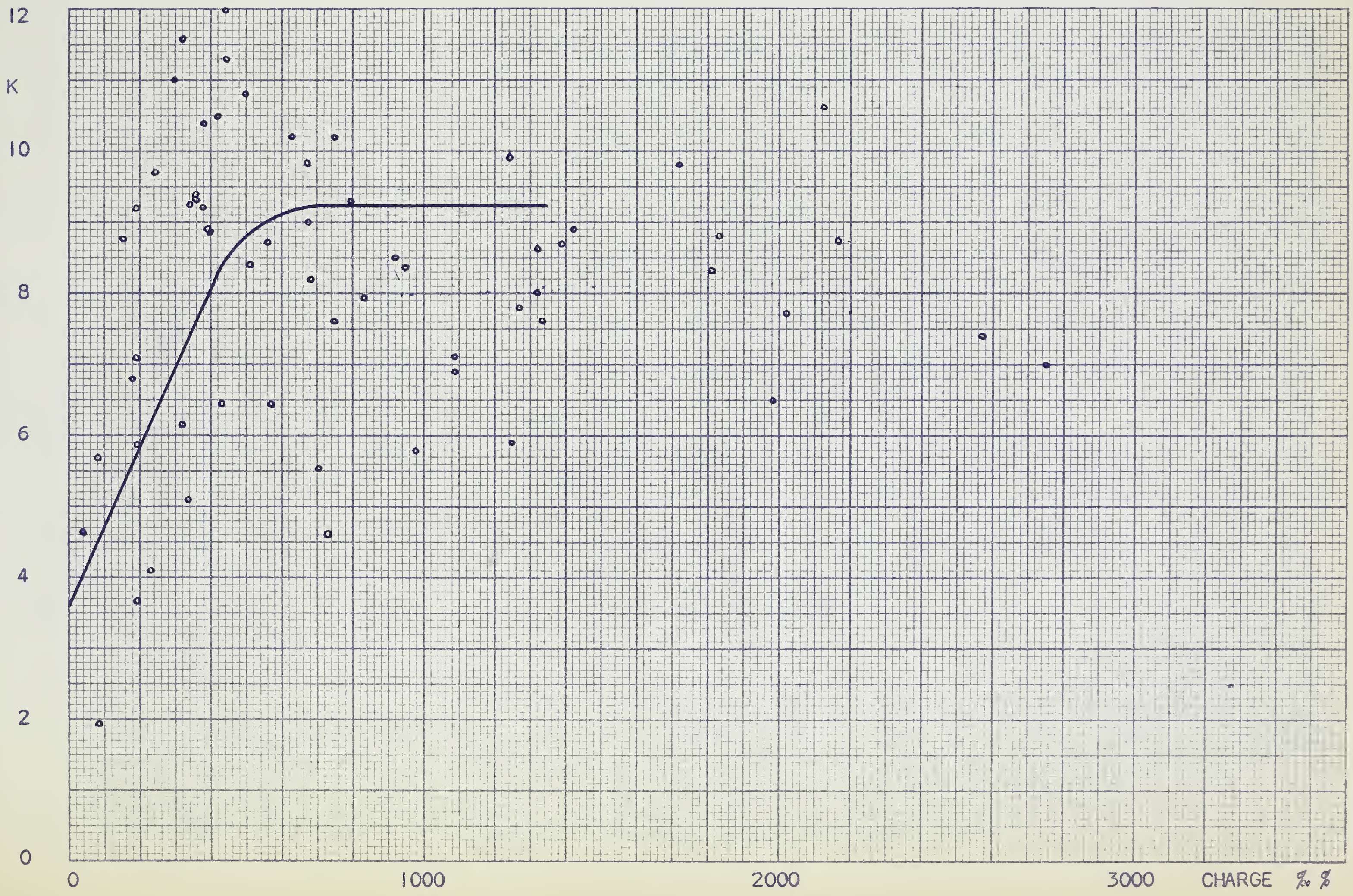


FIGURE 20. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'B'

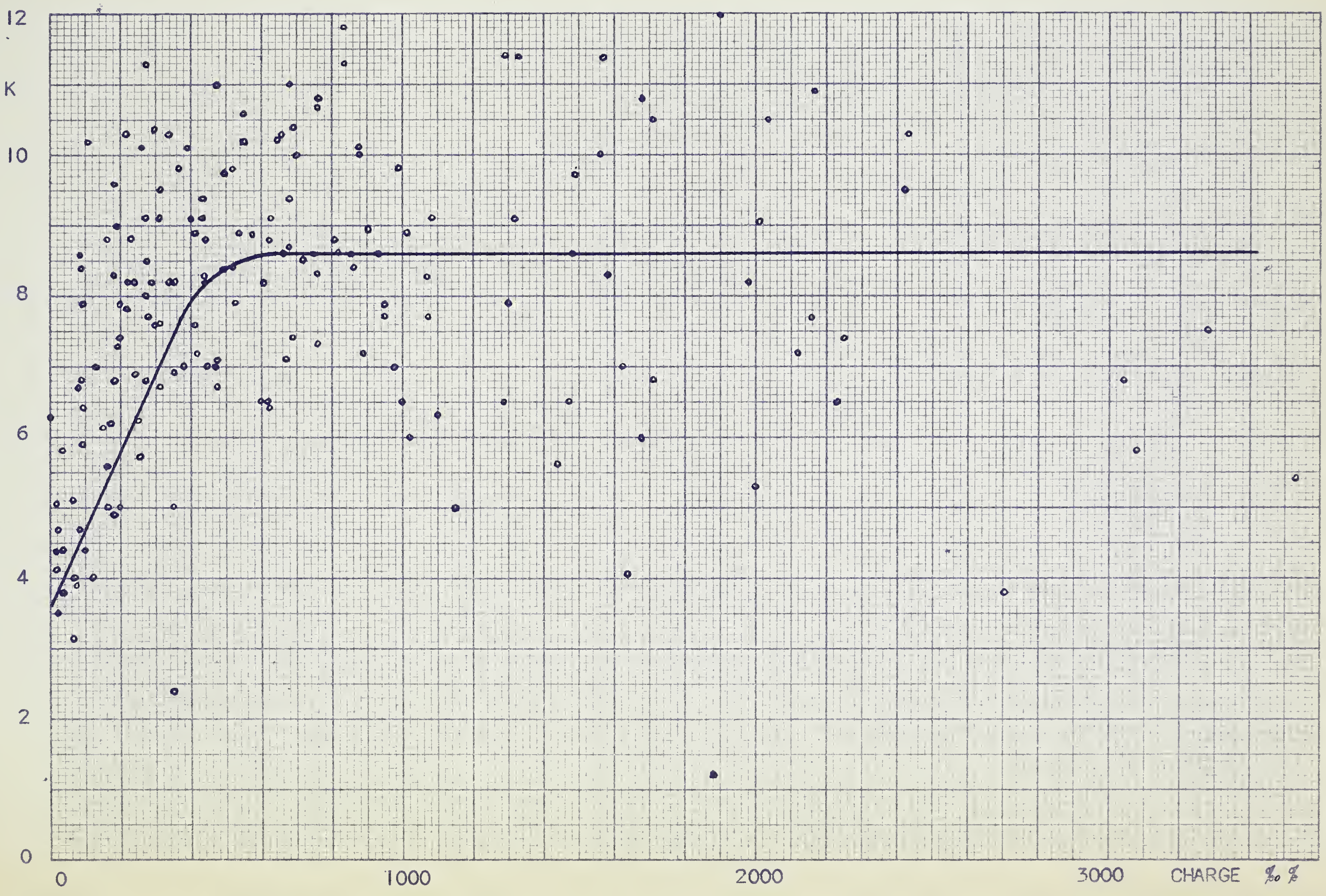


FIGURE 21. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'C'

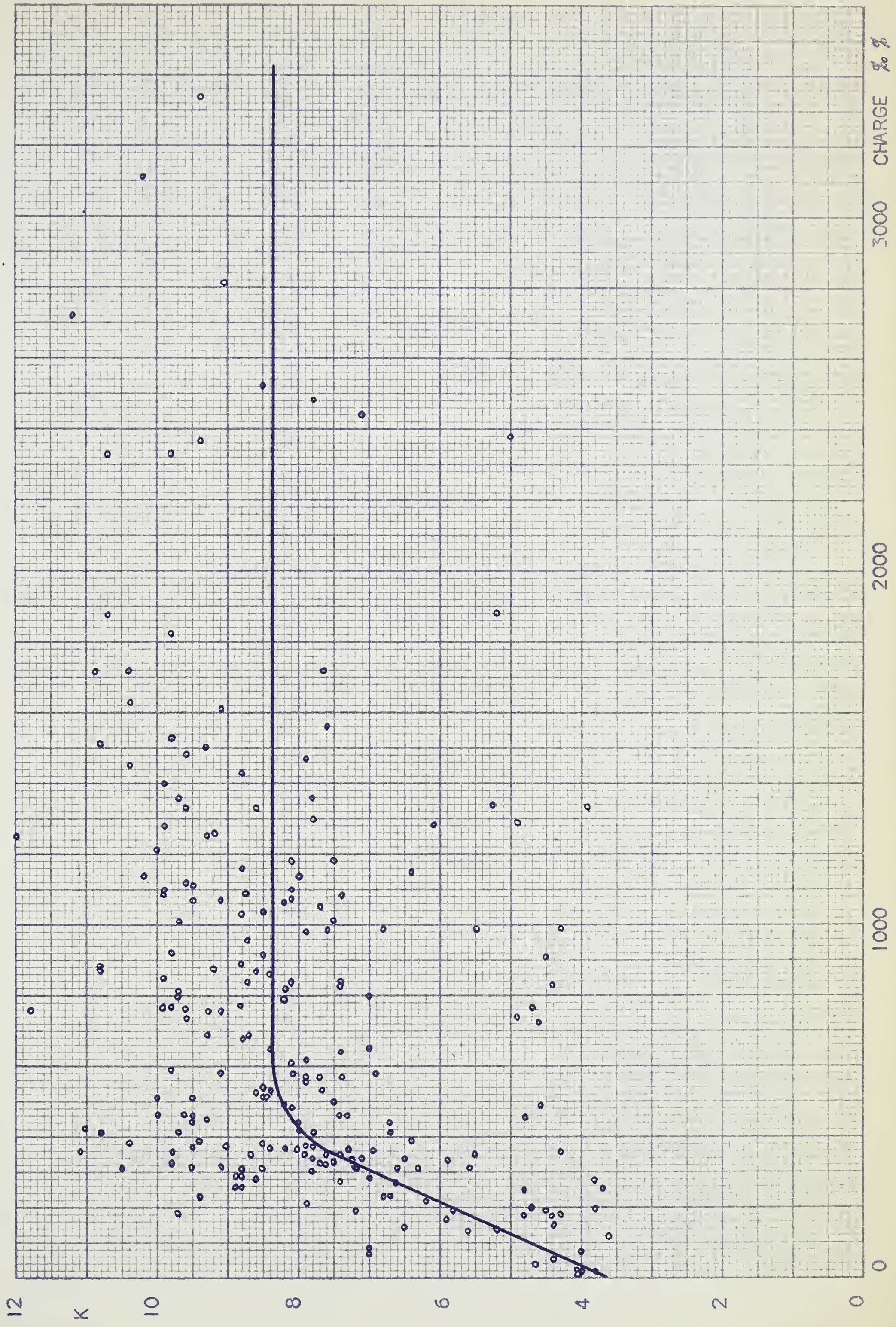


FIGURE 22. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'D'

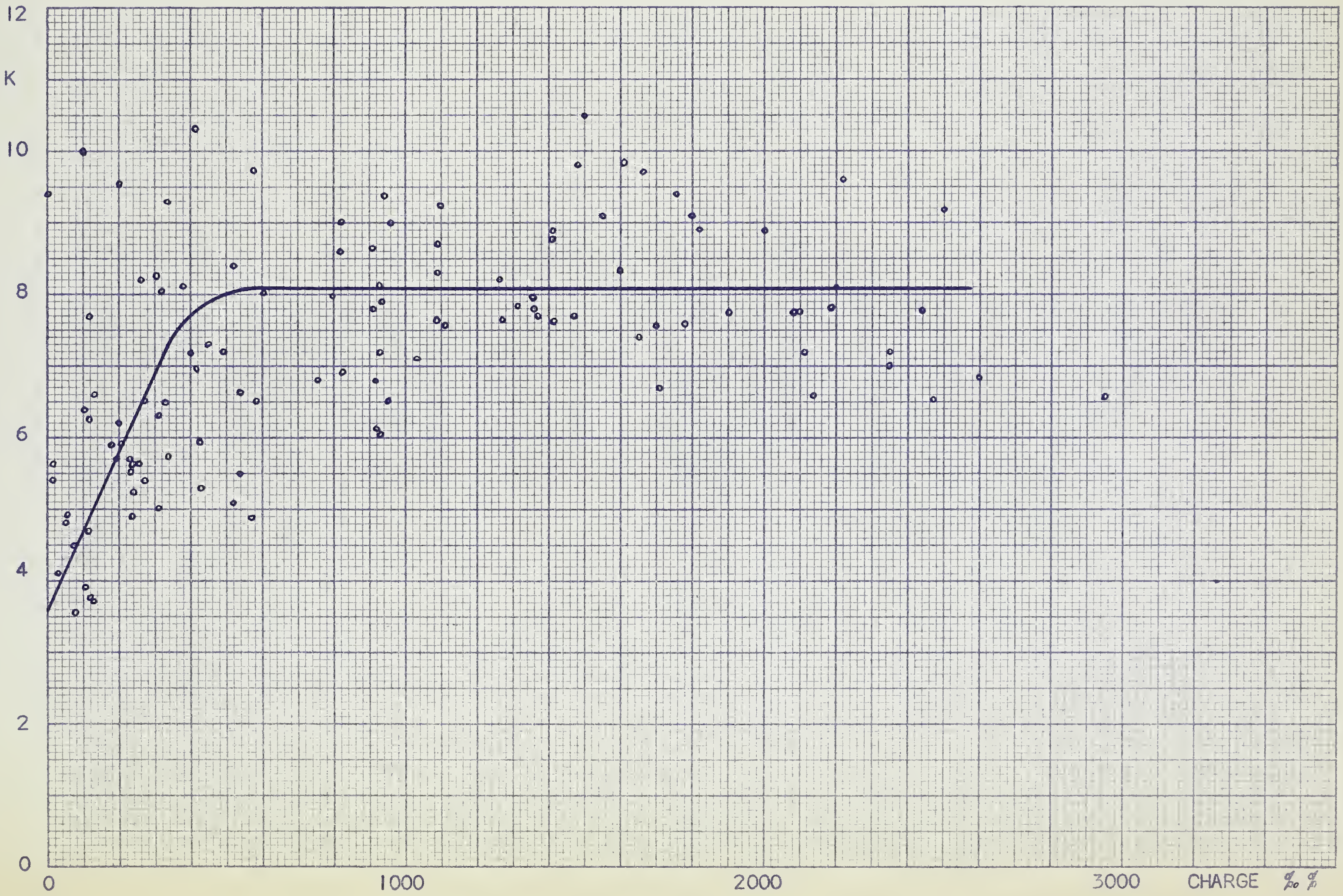


FIGURE 23. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'E'

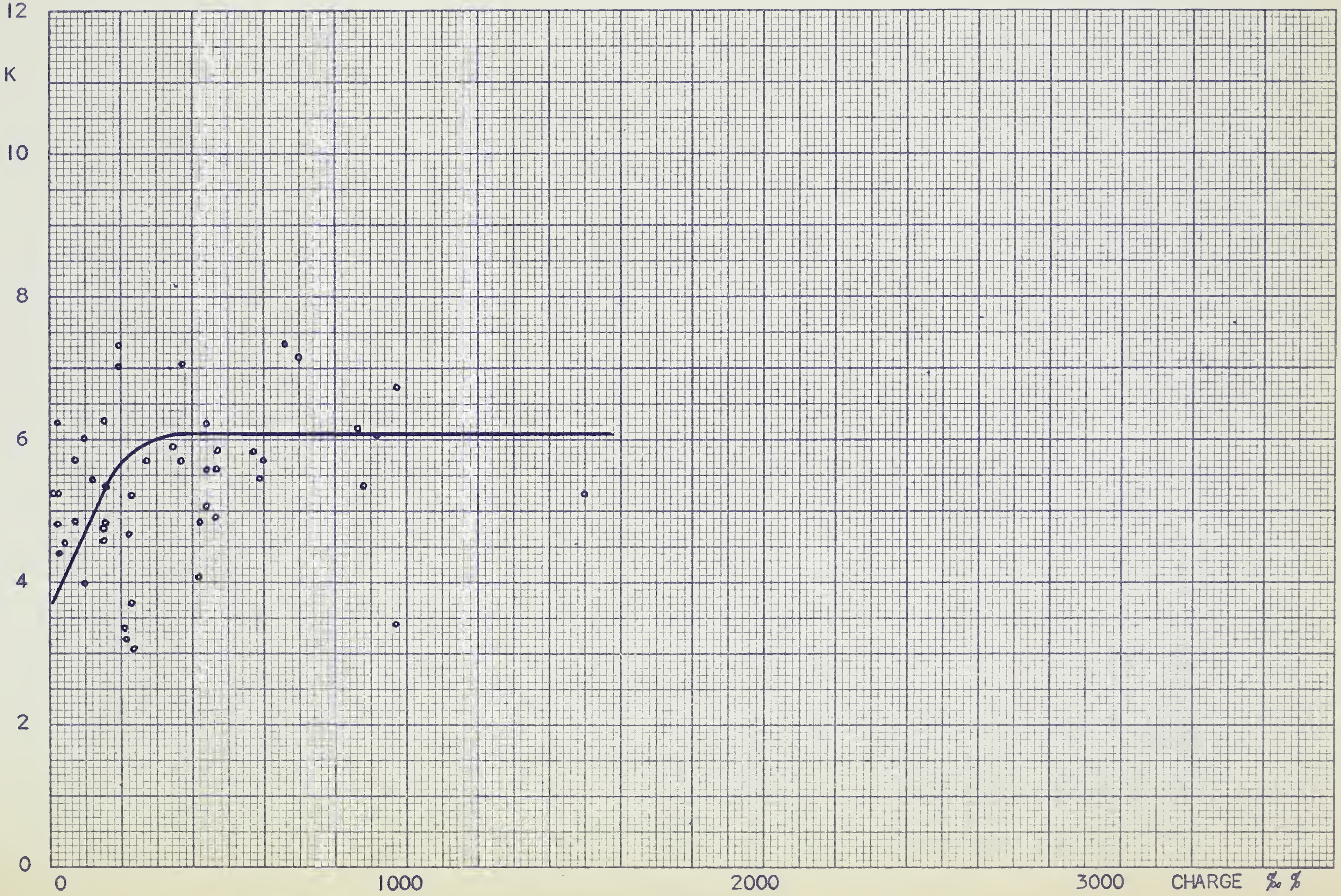


FIGURE 24. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'F'

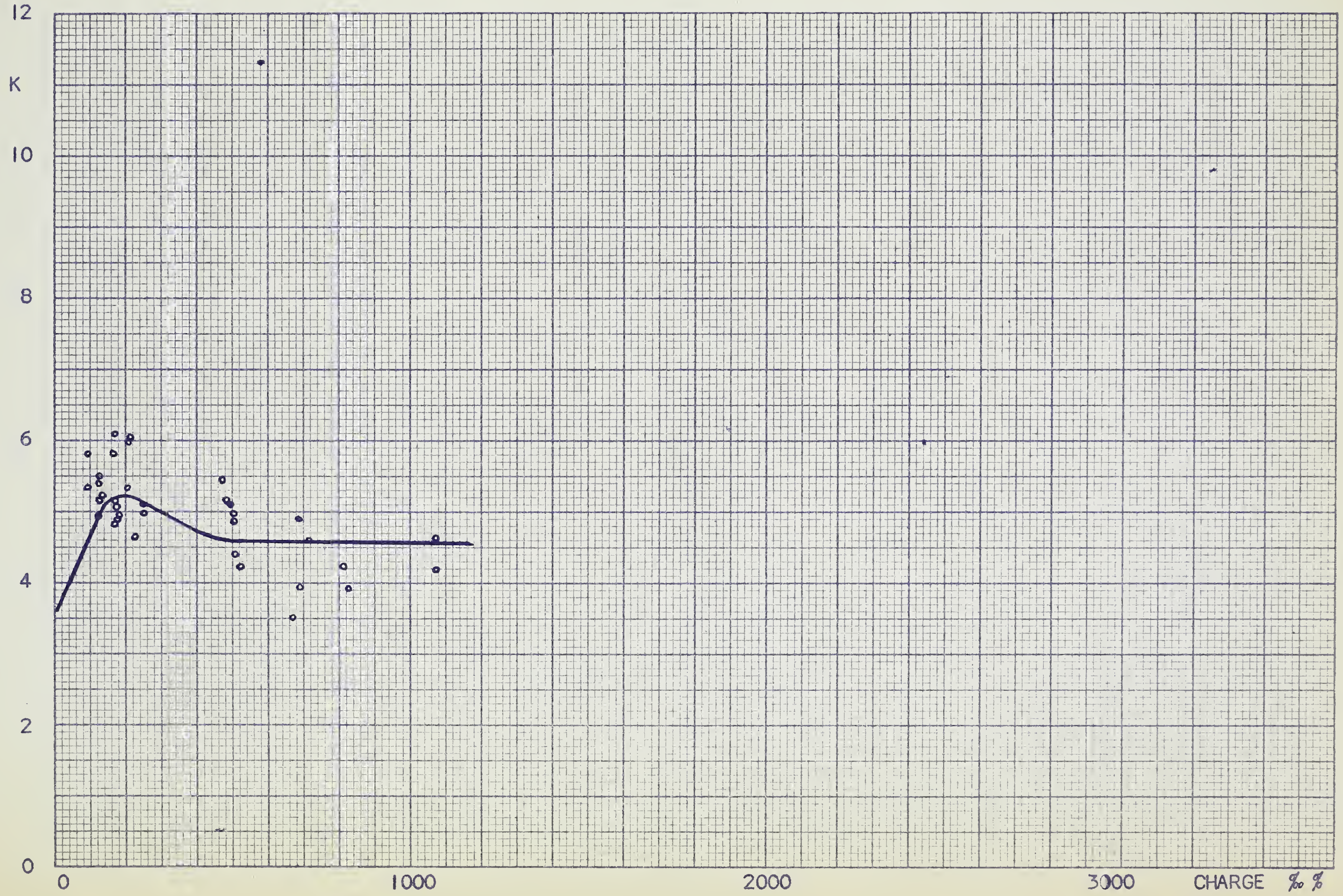


FIGURE 25. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'G'

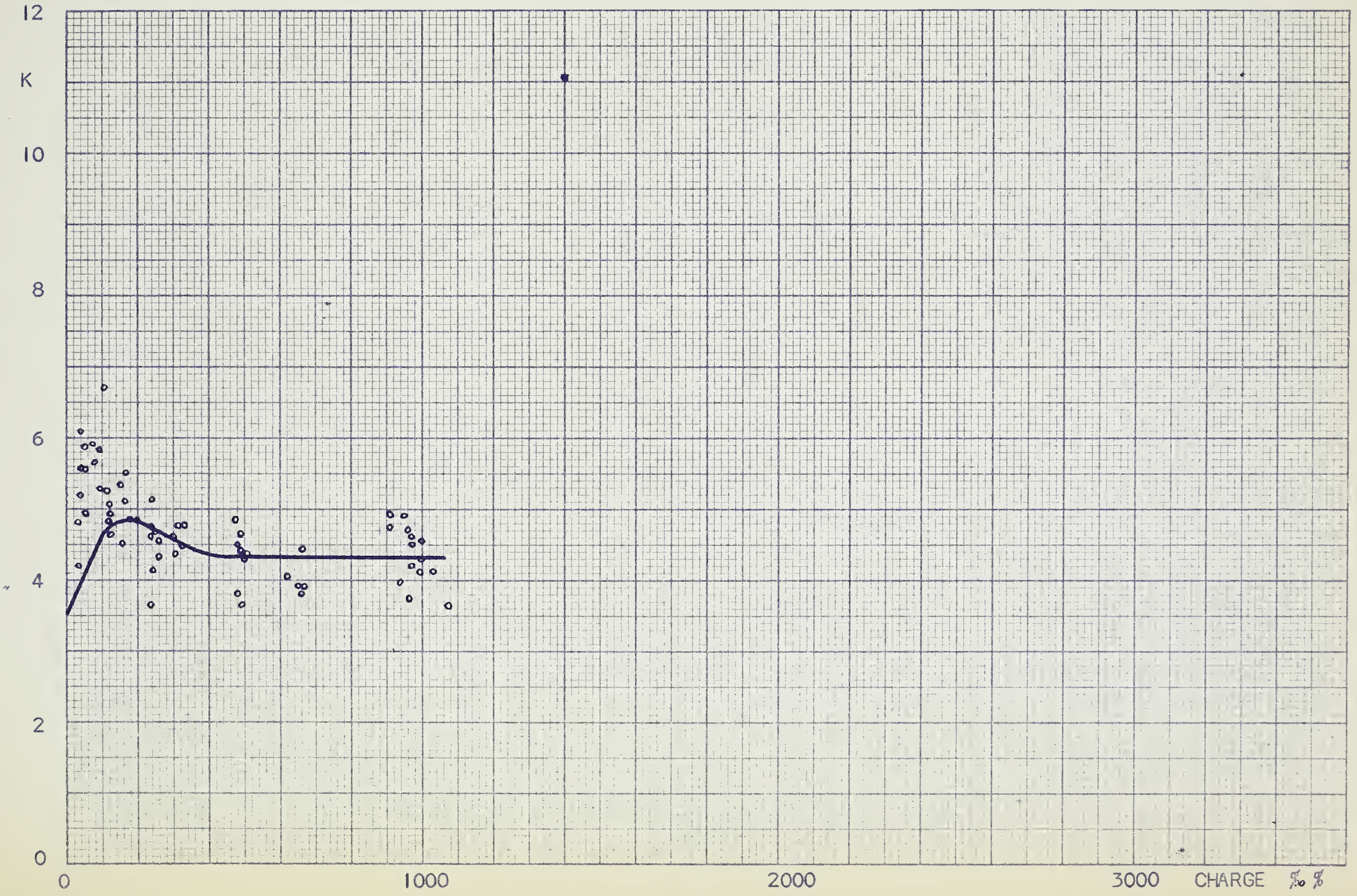


FIGURE 26. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR GILBERT SAND 'H'

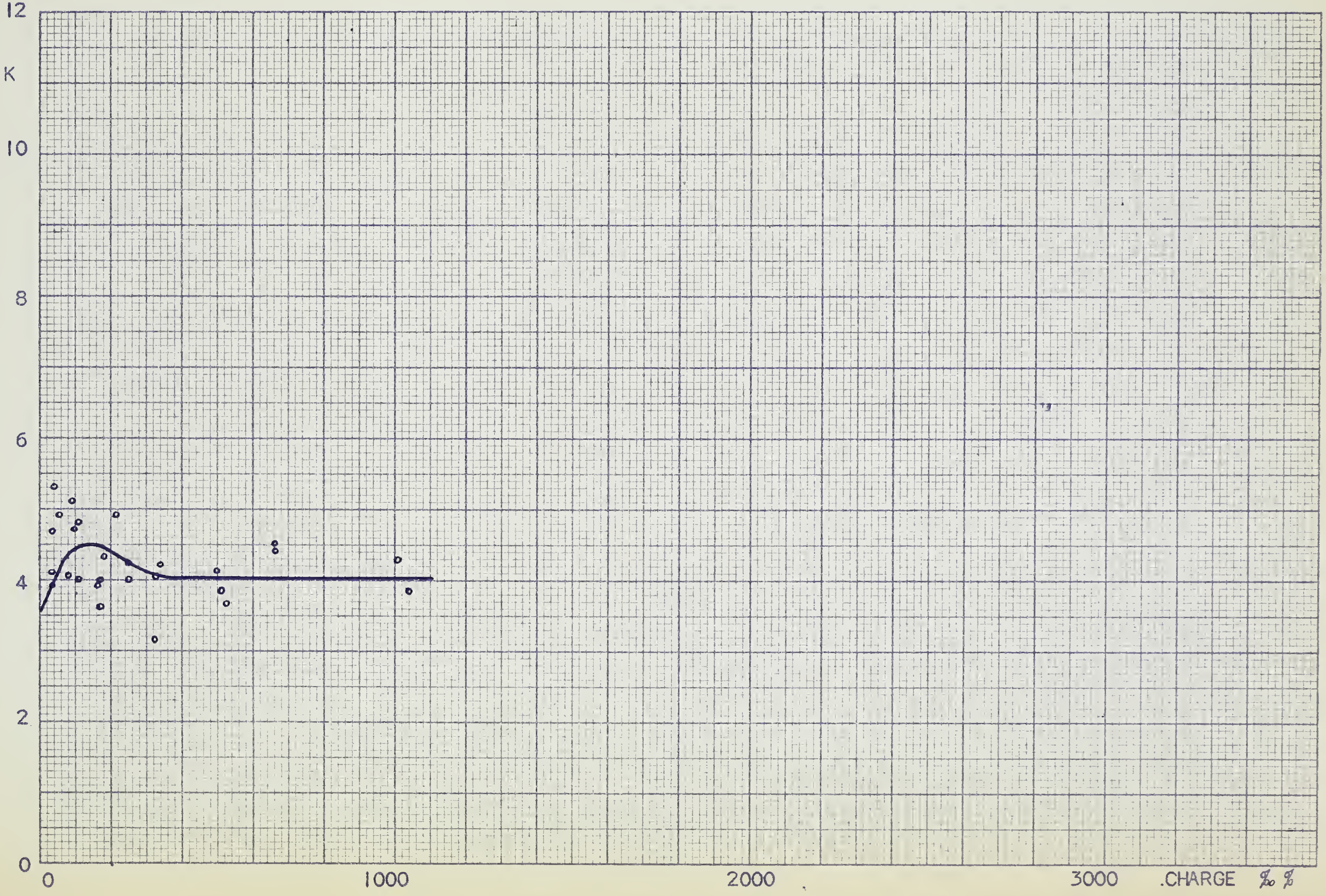
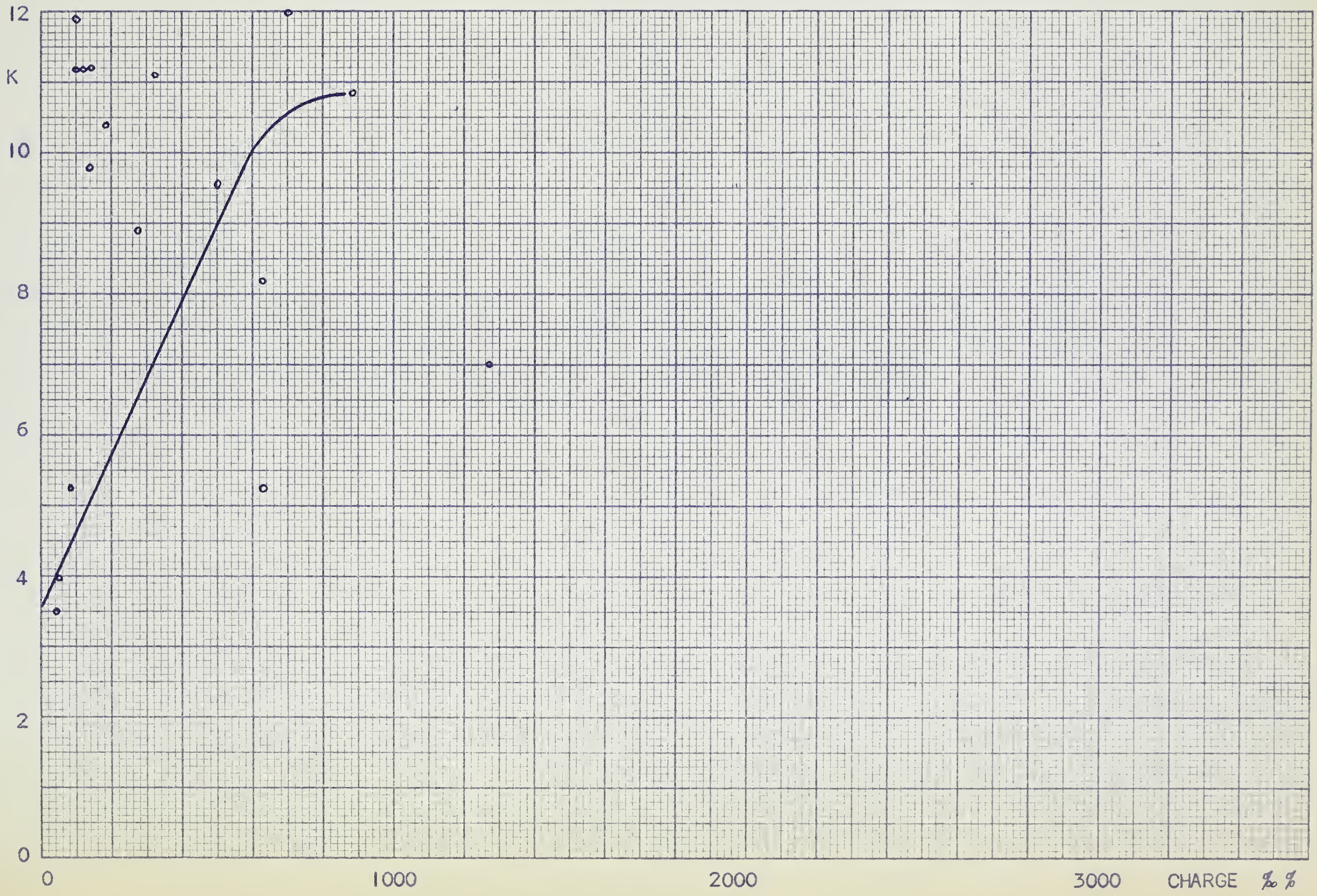


FIGURE 27. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE FOR STRAUB SAND



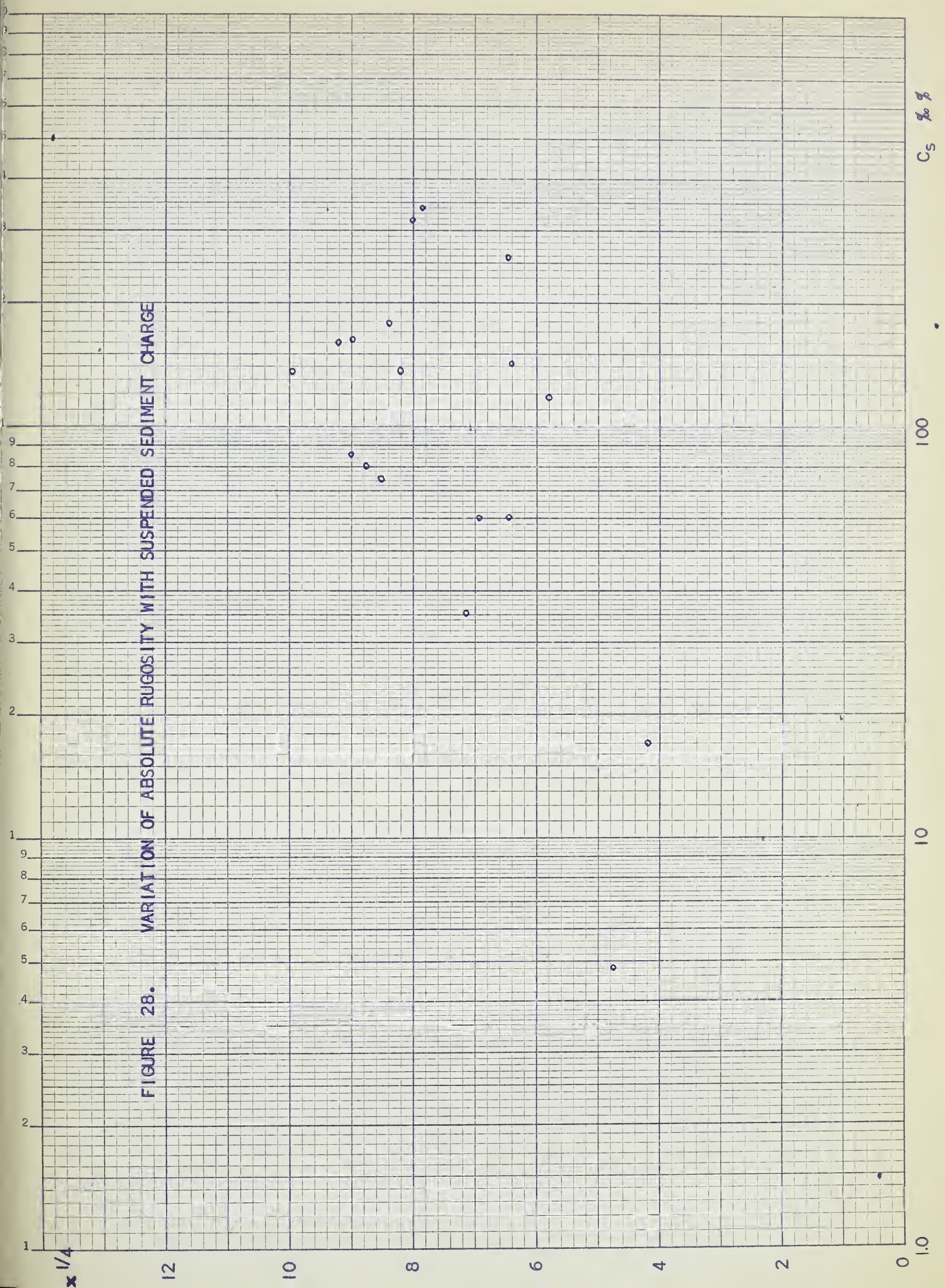


FIGURE 28. VARIATION OF ABSOLUTE RUGOSITY WITH SUSPENDED SEDIMENT CHARGE

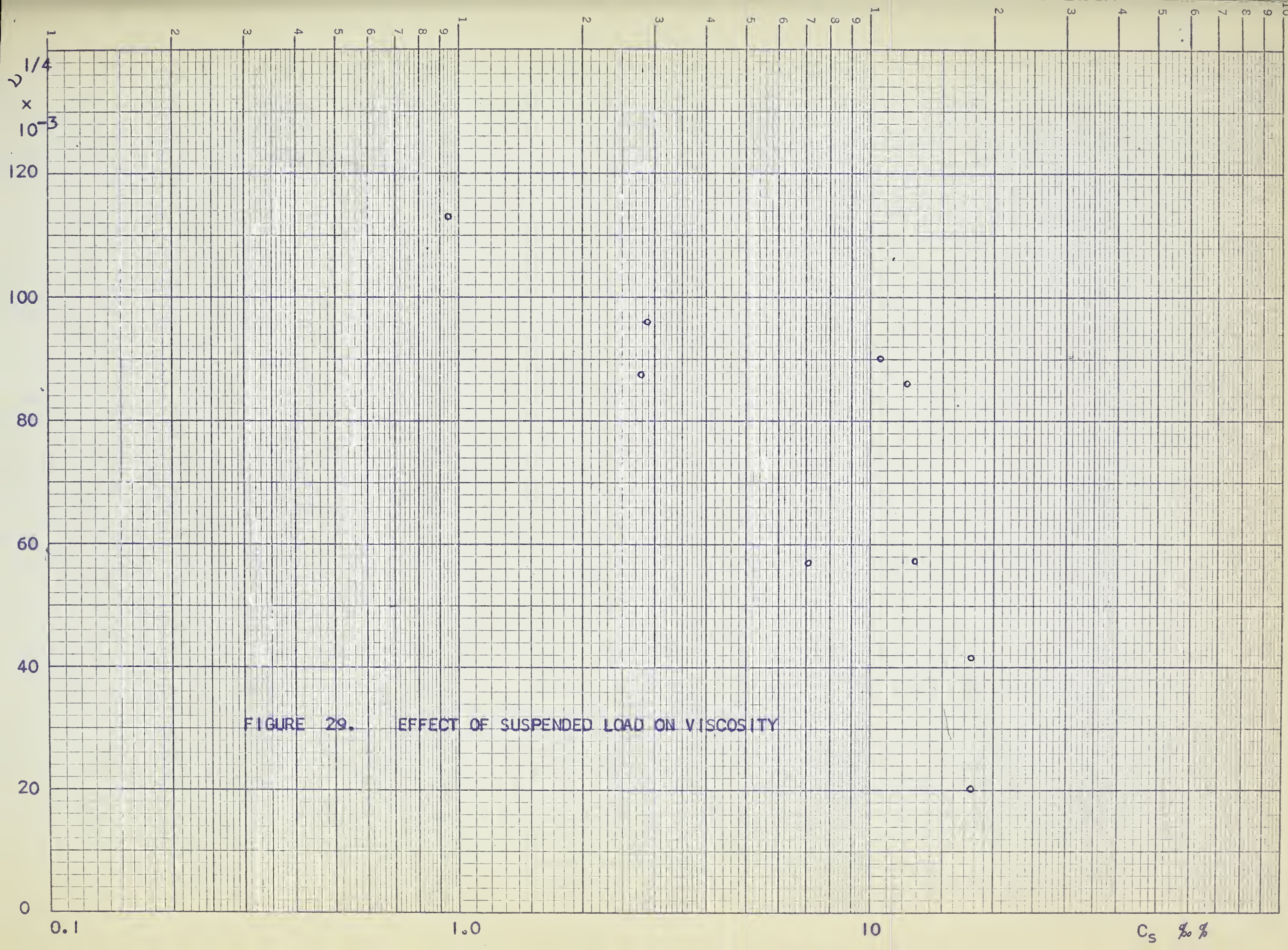


FIGURE 29. EFFECT OF SUSPENDED LOAD ON VISCOSITY